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DEVELOPMENT OF EXPLOSION SUPPRESSION SYSTEM REQUIREMENTS FOR SH--ETC(U)
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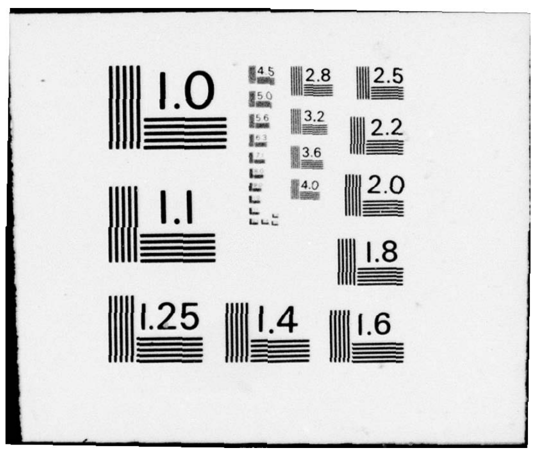
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DEVELOPMENT OF EXPLOSION SUPPRESSION SYSTEM REQUIREMENTS FOR SHIPBOARD PUMP ROOMS

Robert C. Richards

January 1976

Final Report

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16. Abstract

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The results of the explosion suppression test series conducted in the forward pump room of the tanker RHODE ISLAND (internal volume of 18,120 ft^3) are reported. Propane/air and n-Hexane/air mixtures near stoichiometric were used in 10 percent of the pump room volume. The n-Hexane was explosively dispersed and ignited by a propane flame. The unsuppressed tests produced maximum pressures of 12 psig. The suppression attempt was unsuccessful because the pressure detectors, set to trigger the suppression system at 1/2 psig, were too slow.

The propane was injected through two 1/2" pipes and a delay time was provided between injection and ignition to permit the fuel to become quiescent. Upon ignition, the pressure developed very similarly to the n-Hexane explosions and more rapidly than expected. This was finally attributed to obstructions creating turbulence which increased the flame speed and thus the rate of pressure rise. Ultraviolet detectors detected the incipient explosion from 110 to 400+ milliseconds before a pressure detector set for 1/2 psig.

Two explosion suppression systems were tested. They each were based on the following principles: (1) a UV detector "sees" the incipient explosion, (2) the control circuitry fires initiators, (3) the initiators rupture a diaphragm releasing a suppressing agent, (4) the agent is thrown at the flame front, and (5) the explosion is suppressed. In analyzing the tests, the size of the fireball at agent contact, agent breakdown, afterburning and the maximum pressure were considered. The analysis indicates the following minimum application densities (lbs/ft^3) for suppression of these explosions: water, 0.15++; Halon 2402, 0.12+; Halon 1211, 0.06+ <0.09; Halon 1301, 0.05+ <0.08; and Purple K, 0.007.

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1.0 INTRODUCTION

The test program was undertaken in order to examine the feasibility of the concept explosion suppression for the protection of tank vessel pump rooms. It was conducted by the U. S. Coast Guard with industry participation during April through June 1975. The results of the test program will be used in the evaluation of system proposals relative to the acceptance and possible approval of explosion suppression systems for installations on board U. S. merchant vessels.

1.1 Background

Fires and explosions on vessels of all types are inherently difficult to control. The mitigation of the consequences of such events are an even greater design challenge. During the design and operation of vessels great emphasis is placed upon reducing the probability of fire and explosion. Additionally, precautionary systems and procedures are developed and required to protect the consequence of fires and explosions should they occur. Nevertheless, in spite of design efforts and improved operational techniques there have been over 1000 tanker fires/explosions worldwide since 1950[1,2]. The VA FOGG[3] and the SS TEXACO NORTH DAKOTA[4] incidents are two notable examples of disastrous consequences of an unchecked explosion. Figure 1 illustrates some of the damage which can occur.

One of the areas aboard tank vessels which has been prone to explosions has been the pump room. This area is the heart of the cargo transfer system. Cargo pumps, valves, and piping systems with attendant leakage are concentrated in a tanker's pump room(s). On modern Very Large Crude Carriers (VLCC's) it is not unusual to have cargo pumps capable of handling 4000 m^3/hr at 300 meters of head. The energy necessary for cargo transfer coupled with the multitude of flanges and fittings make these spaces prime candidates for conditions conducive to explosion and/or fire. As a result, current design practice requires the fitting of a fixed fire protection system (CO_2, Halon 1301, or water spray), explosion-proof electrical equipment, segregation of pump drivers, and pump room ventilation. Fires in pump rooms have occurred and have been successfully extinguished in many cases by the installed fire protection equipment. None of the required systems, however, were designed for the purpose of inerting a dangerous area nor were they designed to mitigate the effects of a potential explosion. Walsh[2] reports that, "The fires/explosions outside engine spaces and cargo tanks, which include accommodations and pump rooms, were equally divided between fires and explosions." This being the case worldwide, it would appear to suggest the consideration of methods or systems which could prevent serious damage from explosions. It is apparent that if an explosion can be contained without damage to interior equipment or surrounding areas the event, while being totally undesirable, will not in any manner initiate a cascading series of destructive events. The more typical instance, however, probably will result in the rupture of adjacent bulkheads, the fracture of internal piping and the potential release of additional fuel which will serve to increase the overall severity of the event.

A typical scenario that has occurred follows:

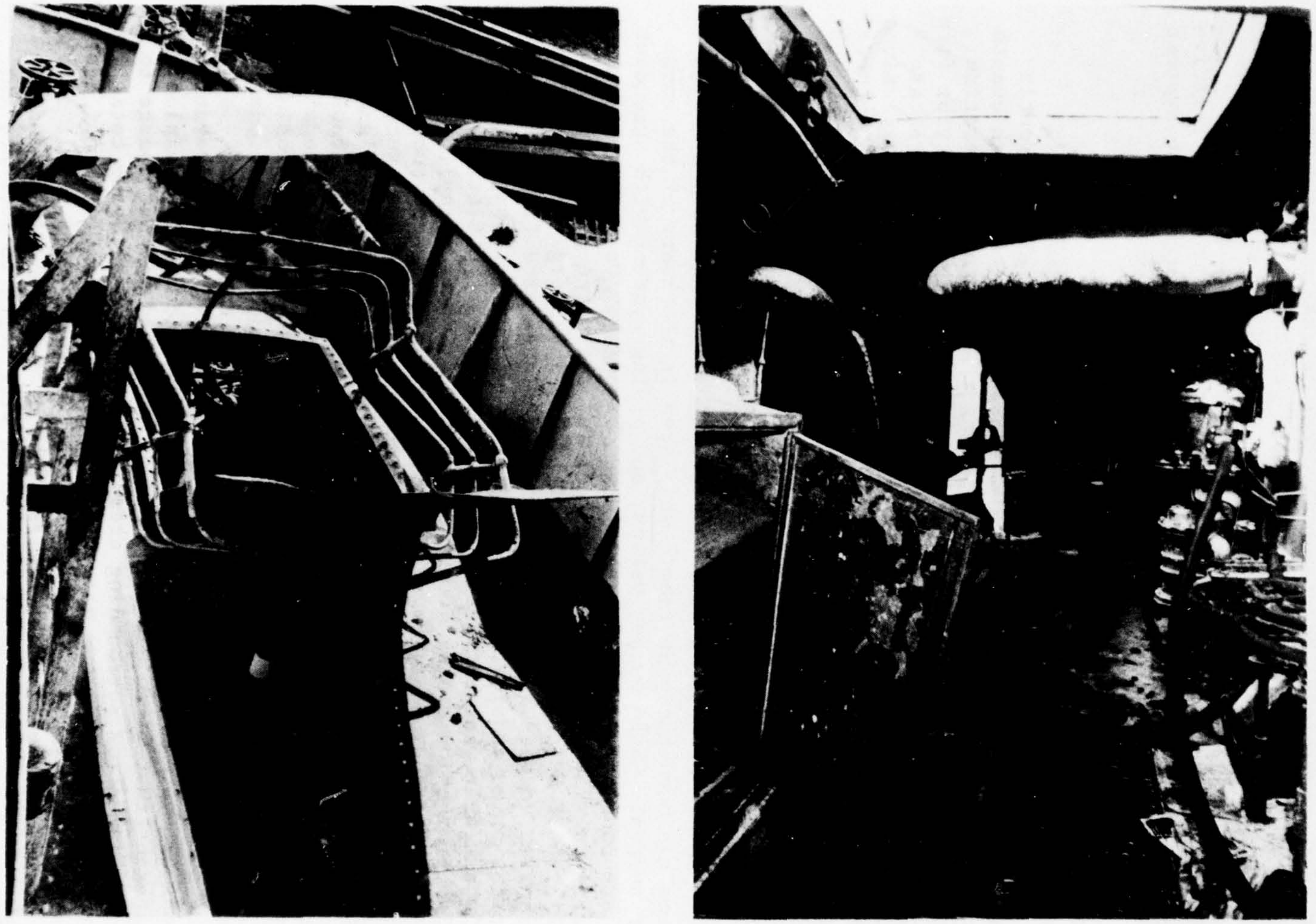


FIGURE 1. Damage as a result of the TEXACO NORTH DAKOTA incident

The vessel is offloading a cargo of high octane gasoline into a shoreside pipeline. Approximately 4 minutes prior to the completion of the offloading, a small leak develops in the flange between the cargo pump and the discharge piping. The gasoline, a low flashpoint liquid, has little trouble vaporizing when injected into the space as a fine mist. The cargo pump runs dry and immediately begins to overheat. Within minutes the flammable mixture surrounding the cargo pump is ignited, setting off an explosion in the pumproom. The pump room access, a door at deck level, which was open, acts as a relief valve for some of the rapidly building pressure. It does not however provide enough vent area and the aft bulkhead separating the pump room from the adjacent machinery space buckles and is breached. The initial explosion weakens the forward bulkhead between the cargo tanks and the pump room. It is buckled allowing volatile gasoline fumes into the machinery space, through the cargo pump room. A flammable vapor cloud reaches an ignition source within the machinery space and a second explosion occurs which engulfs the vessel.

This scenario is not a single casualty but rather a composite of casualties reviewed. It demonstrates the potential results of a pump room explosion.

In examining the problem several potential solutions became apparent. They are:

a. Isolation
b. Advanced inerting
c. Explosion venting
d. Explosion suppression through
   (1) Cooling
   (2) Chemical inhibition

The particular arrangement and uses of many pump rooms in existing ships precludes the first three alternatives without extensive modifications. The program described in this report was an attempt to investigate the potential of explosion suppression as an alternative solution.

1.2 Purpose

These tests were undertaken to evaluate systems which could possibly lead to the improvement in explosion protection of commercial vessels. They were specifically designed to determine if such systems are feasible and, if so, to obtain the minimum requirements for an explosion suppression system used in large volume spaces aboard ships. The tests were conducted with the following objectives:

1.2.1 Determine the effectiveness of various extinguishing agents for explosion suppression in shipboard pump rooms.

1.2.2 Determine the effects of varying extinguishing agent concentration on limiting the pressure rise for suppressed explosions.

1.2.3 Obtain sufficient data to permit the evaluation of explosion suppression system designs for large volumes.

1.2.4 Determine the detection and agent dispersal parameters for effective pump room explosion suppression systems.

1.3 Limitations

An inherent problem in full-scale explosion testing is the inability to exactly duplicate all of the variables which effect the explosion. This in turn leads to a lack of repeatability of the results. In this test program every effort was made to control the quantity of fuel, quantity of suppression agent, the volume of the pump room (by maintaining the bilge water at a constant level), and the explosion venting ratio. The variables which could not be controlled include environmental factors such as the temperature in the pump room which ranged between 70 and 90°F (21 and 32°C) and the relative humidity in the pump room. Due to funding limitations, it was not possible to replicate the suppression tests and thus only one data point for each agent concentration was obtained. However, it is believed that test results reported herein could be repeated to within ± 10 percent which is considered adequate for tests of this nature.

2.0 DESCRIPTION OF UNSUPPRESSED EXPLOSION TESTS

All testing was conducted at the U. S. Coast Guard Fire and Safety Test Facility in Mobile, Alabama on board the 8,500 gross ton T-1 tanker M/V RHODE ISLAND. This tanker is 490 feet (150m) long with a 65-foot (20m) beam and uses two pump rooms for the loading, unloading and distribution of cargo. The full-scale explosions were conducted in the forward pump room as shown in Figure 2.

2.1 Pump Room Characteristics

The pump room is located between the bow and the forward deck house. It consists of a trunk which is approximately half the width of the ship and located on its center line. Two wing spaces open into the lower quarter of the trunk and extend to the full beam of the ship, port and starboard. A small deck house is located on the main deck level above the trunk. The arrangement of the pump room is shown in Figure 3. During the majority of the testing, the bilge water level was maintained at 52 inches below the lowest catwalk level. For these tests the total volume of the pump room and wings was 18,120 cubic feet ($513m^3$). This figure does not include the volume occupied by the machinery (which is estimated at 10%) because these volumes are not considered in the design calculations for fire extinguishment systems.

The machinery equipment and catwalks within the pump room presented numerous obstructions to the development of the fire ball during an explosion. The obstructions which appear to have the most significant effect were the three large pump casings (located between 24 and 76 inches (0.6 and 1.9m) above the bilge water) and the lowest catwalk (located 52 inches (1.32m) above the bilge water) which was constructed of steel diamond plate laid in angle iron frames. These obstructions can be best observed in Figure 4.

There were several possible unrestricted relief vents in the pump room. They included the two vent stacks which can be seen in Figure 2,

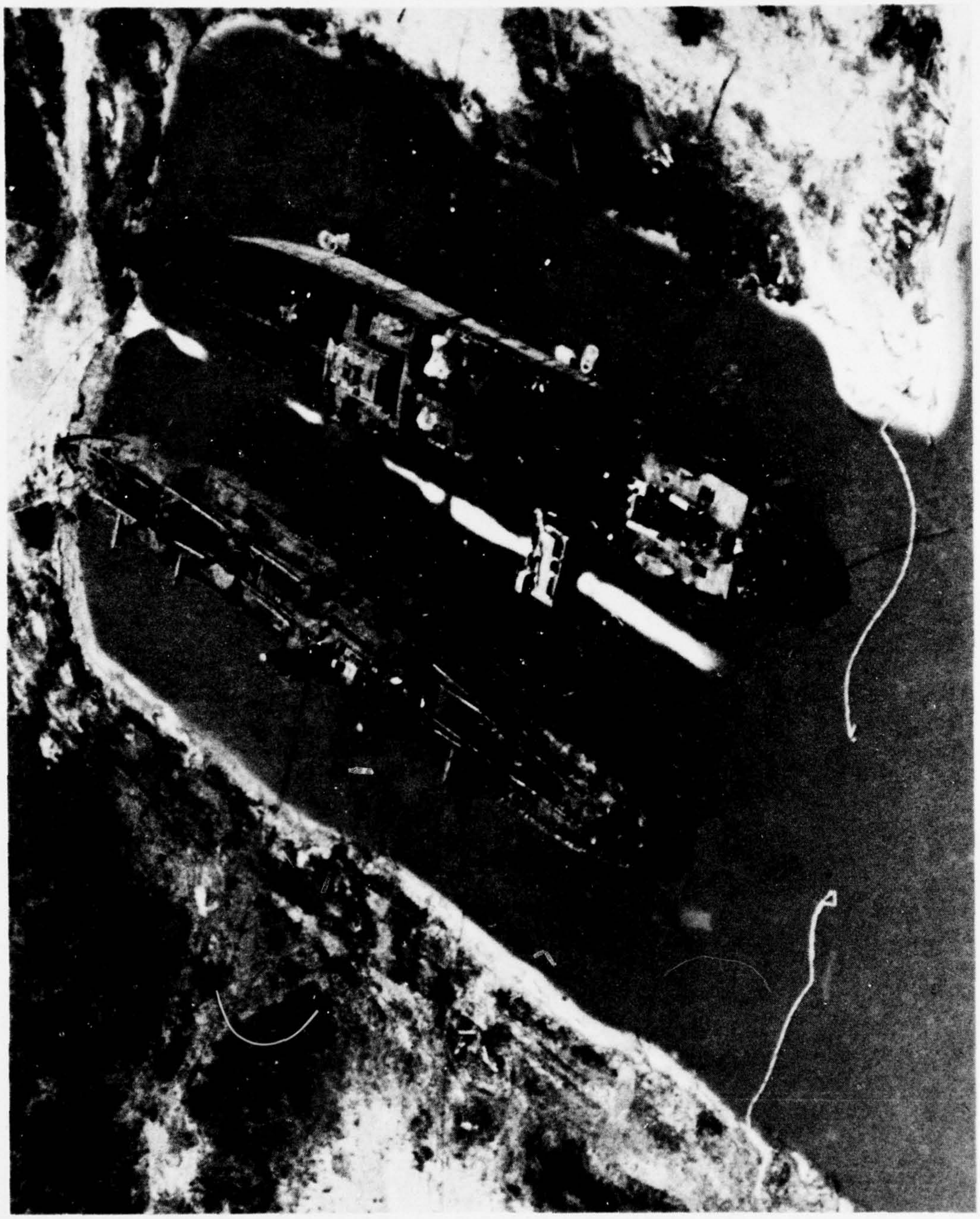


FIGURE 2. Test ship M/V RHODE ISLAND (on right)

An explosion in the pump room of M/V RHODE ISLAND

the door and the hatch on the deck house. The door and the hatch normally would be closed during pump room operations while the vents are open and used for forced ventilation. The internal ventilation ducting which is connected to the vent stacks collapsed during the first few unsuppressed explosion tests thus sealing them off. Thereafter they did not provide an unrestricted explosion vent during the remainder of the test series. The open areas through the main deck which were inside the pump room deck house (see Figure 3) permitted the hot gases to escape from the pump room. Their escape was limited only by the deck house door and hatch which were open. Together these provided 32 square feet ($2.97m^2$) of venting area. For volumes similar to the size of this pump room, explosion vent ratio recommendations require at least 3.3 square feet ($0.31m^2$) of venting for every 100 cubic feet ($30.5m^3$) of internal volume[5,6]. Since the vent ratio in these tests (0.18 square feet ($0.017m^2$) per 100 cubic feet ($30.6m^3$) of volume) was an order of magnitude smaller than this recommendation, venting was not expected to have a significant effect on the tests. This was verified in Tests U1 through U2, U19, and U20. (Note: U designates an unsuppressed explosion test and S designates an explosion suppression attempt in this report.) In these tests the vent ratio was systematically varied by opening and closing the door and hatch. No detectable effects on the maximum explosion pressures were observed. Thus the majority of the unsuppressed and all of the suppressed explosion tests were conducted with both the door and hatch fully opened.

2.2 Test Methods and Instrumentation

A primary consideration in designing the test procedure was to minimize the damage which might result from the test explosions and yet still obtain realistic data. Accordingly all tanks surrounding the pump room were gas freed to preclude the possibility of secondary or multiple explosions. If the test explosion were designed for a stoichiometric mixture of the hydrocarbon fuel (either Hexane or propane) in air throughout the entire volume of the pump room, then 120 psig[7] ($8.44\ Kg/cm^2$) would be expected and the pump room would not survive one test. Based on the design limitations of the pump room bulkheads, it was decided that the pump room could withstand a maximum of 15 psig ($1.05\ Kg/cm^2$). The following calculation shows that if the stoichiometric mixture of a hydrocarbon fuel were placed in 10 percent of the volume and ignited, then the expansion of the explosion into the remaining 90 percent of the volume would limit the theoretical maximum pressure to 12 psig ($0.84\ Kg/cm^2$).

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where: P_1 = pressure created by a stoichiometric mixture of a hydrocarbon fuel $\simeq$ 120 psig ($8.4\ Kg/cm^2$).

V_1 = volume in which the pressure P_1 is created = 10% of test volume.

T_1 = temperature at which P_1 is created $\simeq T_2$.

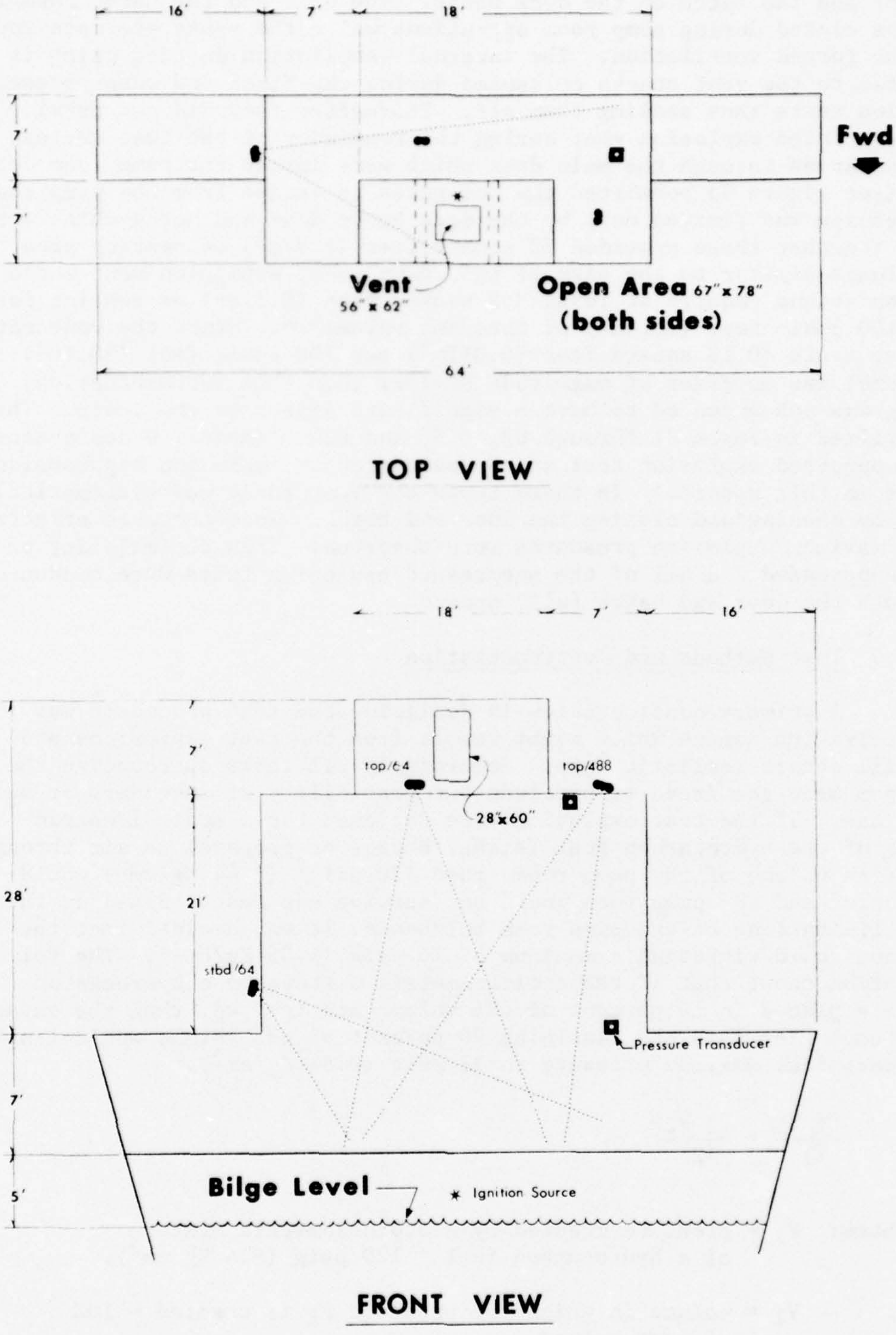
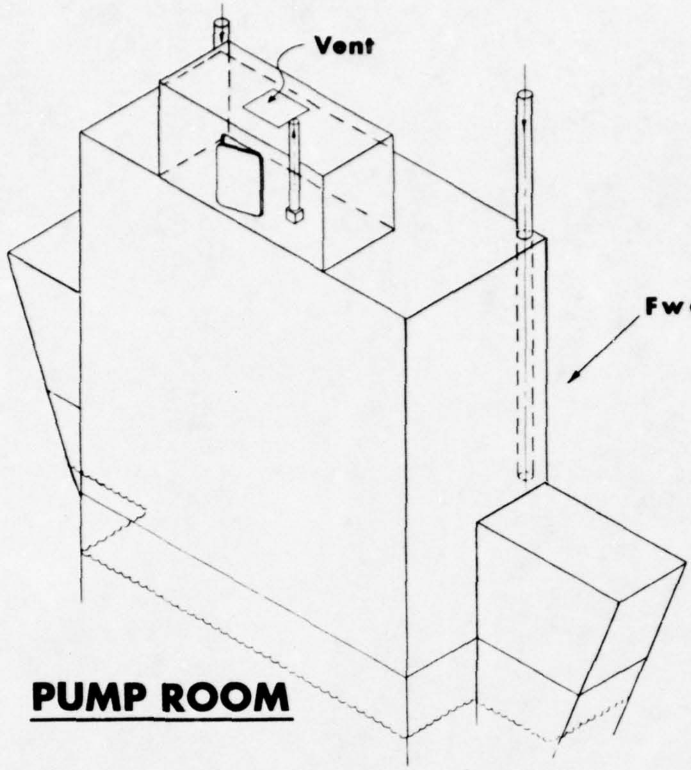
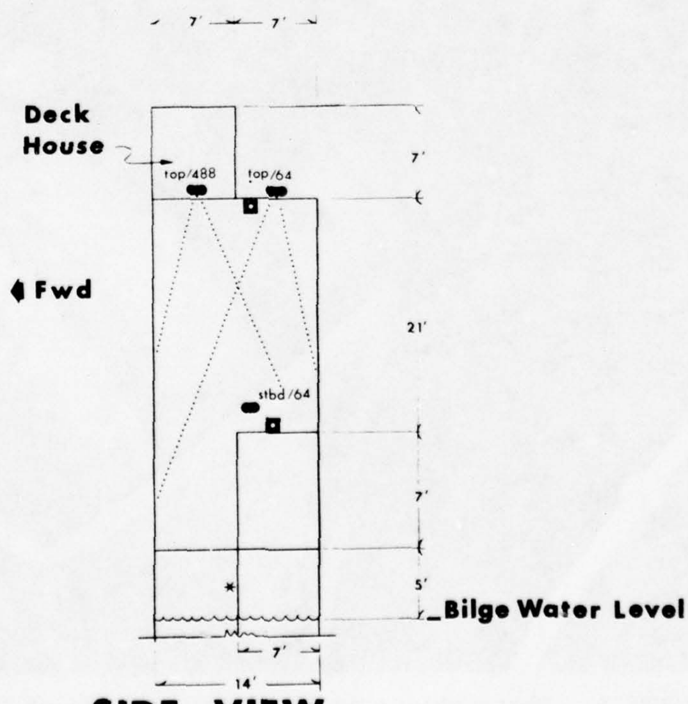


FIGURE 3. Pump room arrangement showing camera, pressure transducer and ignition source locations (2 pages)



PUMP ROOM



SIDE VIEW

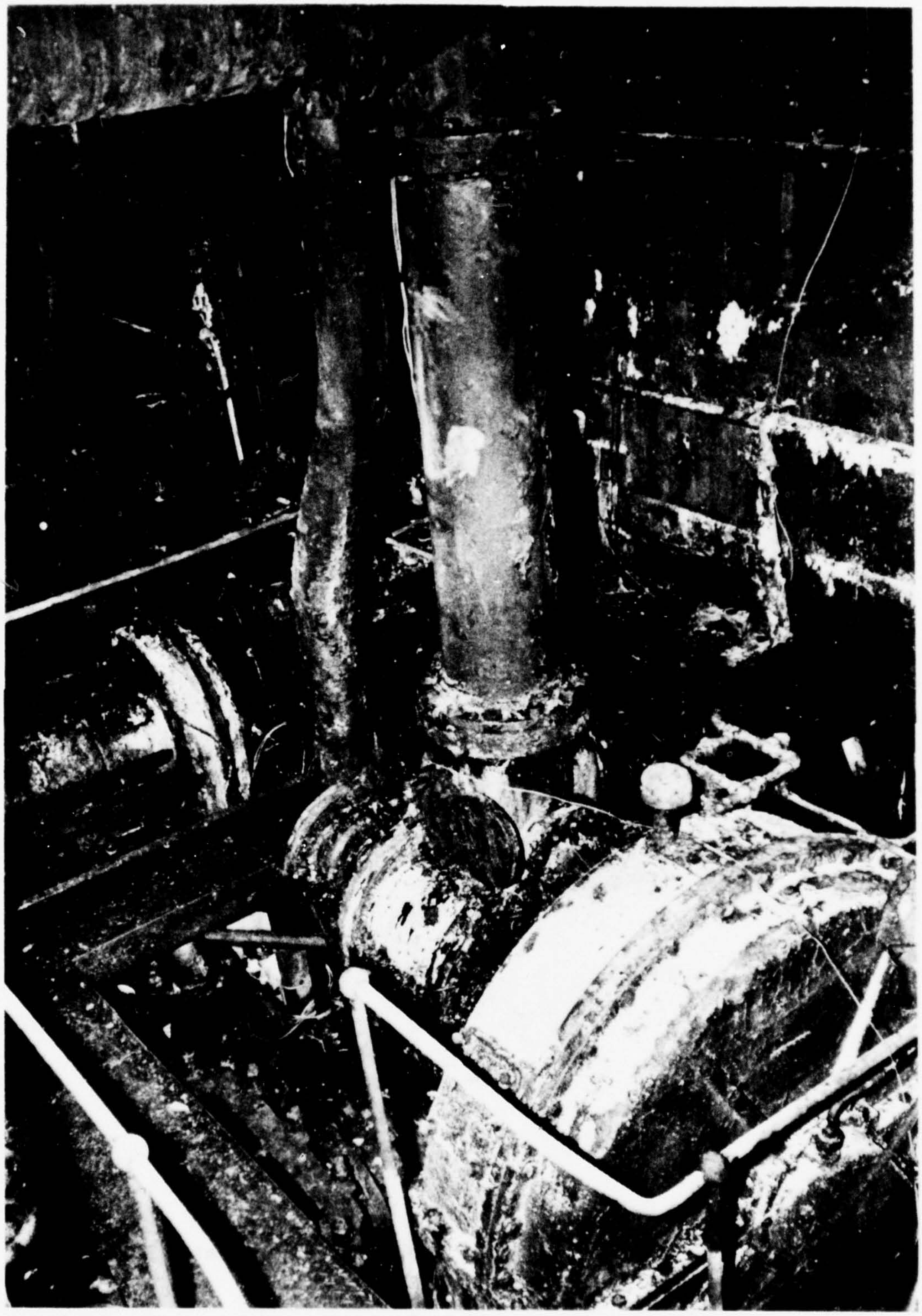


FIGURE 4. Obstructions in the lower portion of the pump room

P_2 = pressure in test vessel.

V_2 = volume of test vessel.

$\therefore$ $120 \times 10 = P_2 \times 100$ and $P_2 = 12$ psig (0.84 Kg/cm^2).

A successful explosion suppression should hold the maximum explosive pressure to substantially less than 5 psig (0.35 Kg/cm^2). Thus it was reasoned that this method of limiting the volume of explosive mixture to 10 percent of the total volume would produce realistic results for explosion suppression purposes.

One would expect the test explosion to follow curve B in Figure 5. It should be noted that curve B is indistinguishable from curve A up to approximately 10 psig (0.7 Kg/cm^2). One can further be convinced that this method is realistic by considering the explosion from the fireball's point of view. As it is ignited and begins to grow, it consumes only stoichiometric fuel air mixture at its exterior surfaces. It is not until the fireball has expanded to fully encompass the mixture that it realizes the entire volume of the pump room is not included. Thus the beginning stages of its growth would be the same as if it were initiated in a stoichiometric mixture occupying 100 percent of the volume. Some work that tends to support this theory was conducted by the Bureau of Mines[8]. In their tests, stoichiometric mixtures of methane were introduced into 100 percent of the test enclosure and ignited. These explosions were successfully suppressed by extinguishing the localized fireball in approximately 10% of the volume and maintaining the pressure below 1 psig (0.07 Kg/cm^2). Thus the stoichiometric mixture in the remaining 90% of the volume had no effect on the explosion.

Ignition Sources - Three types of ignition sources were used throughout the test series. They were: a flame igniter; a spark igniter; and a hot wire igniter. The flame igniter consisted of a small propane torch as used in home shops which was charged with NGPA grade hd-5 propane. This torch had a cylindrically symmetrical tip which produced a pencil flame approximately 1/2 inch (1.3 cm) in diameter and 4 ± 1/2 inch (10.2 ± 1.3 cm) in length. It was used exclusively for igniting the Hexane test fuel in tests U1-U12, U28 and S1. The spark igniter was a unit normally employed for lighting gas ranges. It employed a 1.5 micro farad capacitor at 120 volts to store the energy. This gave a maximum stored energy of 17 joules and an exact spark energy of 2 to 3 joules. This igniter was employed for the propane explosion tests U13-U27, U29, U30, and S2-S10. The hot wire igniter consisted of two commercially available NiCrome wire resistance heaters. They were powered by 120 volts and produced a nominal 2,000 watts per heater. This ignition source was used for the explosion tests U31 and S11-S14. It should be pointed out that neither the spark igniter nor the hot wire igniter had a detectable effect on the development of the propane fireball and ensuing explosion since neither source was large enough to initiate a detonation. Thus, they can be considered equivalent ignition sources.

Pressure Measurement - The internal pressure in the pump room was monitored with two bonded strain gage pressure transducers. These transducers were calibrated over the range of 0 to 10 psig (0 to 0.7 Kg/cm^2) and were

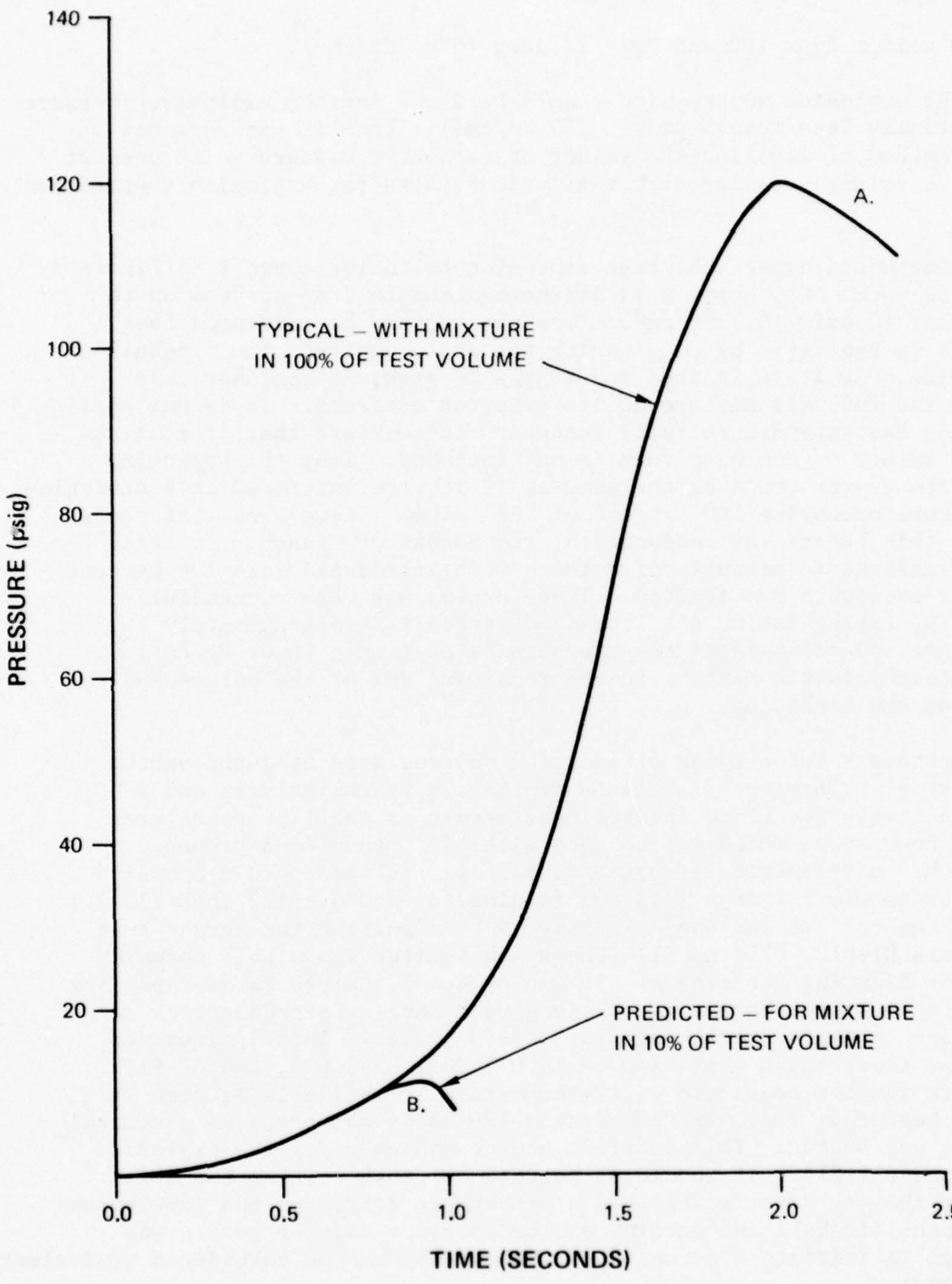


FIGURE 5. Pressure-time traces for explosions of stoichiometric mixtures of paraffin hydrocarbons in air

accurate to ± 0.2 psig. They were located for all tests as follows: lower transducer - 204 inches (5.18m) above bilge water level, 48 inches (1.29m) aft of the forward bulkhead, and 149 inches (3.78m) port of the center line; upper transducer - 436 inches (11.07m) above the bilge water, 62 inches (1.57m) aft of the forward bulkhead and 147 inches (3.73m) port of the center line as shown in Figure 3. This upper transducer was located immediately below the main deck. A recording oscillograph equipped with a carrier amplifier was used to record the explosion pressures. Timing markers were electronically superimposed on the oscillograph chart.

Photography - Motion picture photography was used to record both internal and external events during the explosion tests. All cameras used 16 mm film and were located as follows:

CAMERA DESIGNATION	LOCATION (in/m)			FRAMING RATE (fps)
	HEIGHT ABOVE BILGE WATER	DISTANCE AFT OF FWD BULKHEAD	DISTANCE FROM CENTERLINE	
Deck	Forward Deck House aimed fwd across Pump Room Deck House			64
Top/64	488/12.39 Main Deck	126/3.2	57/1.45 Stbd	64
Top/488	488/12.39 Main Deck	56/1.42	150/3.81 Port	488
Stbd/64	167/4.24	86/2.18	185/4.7 Stbd Stbd Blkhd	64

The three internal cameras were all aimed at the vicinity of the ignition source as shown in Figure 3.

2.3 Hexane Explosion Characteristics

Safety precautions during the fueling of the Hexane explosions were carefully observed. The guidelines for introducing the proper mixture of Hexane and air indicated that it should be done remotely, and as rapidly as possible, and would vaporize a large percentage of the liquid Hexane. To accomplish this a method of suspending one gallon plastic containers of Hexane within the pump room and blowing them apart with initiators was employed (see Figure 6). This system permitted remote distribution of the Hexane and reasonably uniform distribution throughout approximately 10 percent of the volume of the pump room. It was somewhat realistic in the sense that it approximated a fuel spray from a ruptured line. It did, of course, produce a turbulent cloud of Hexane mist.

To determine what the turbulence in this mist was, a dispersion test was conducted using a one-gallon container filled with water. Three

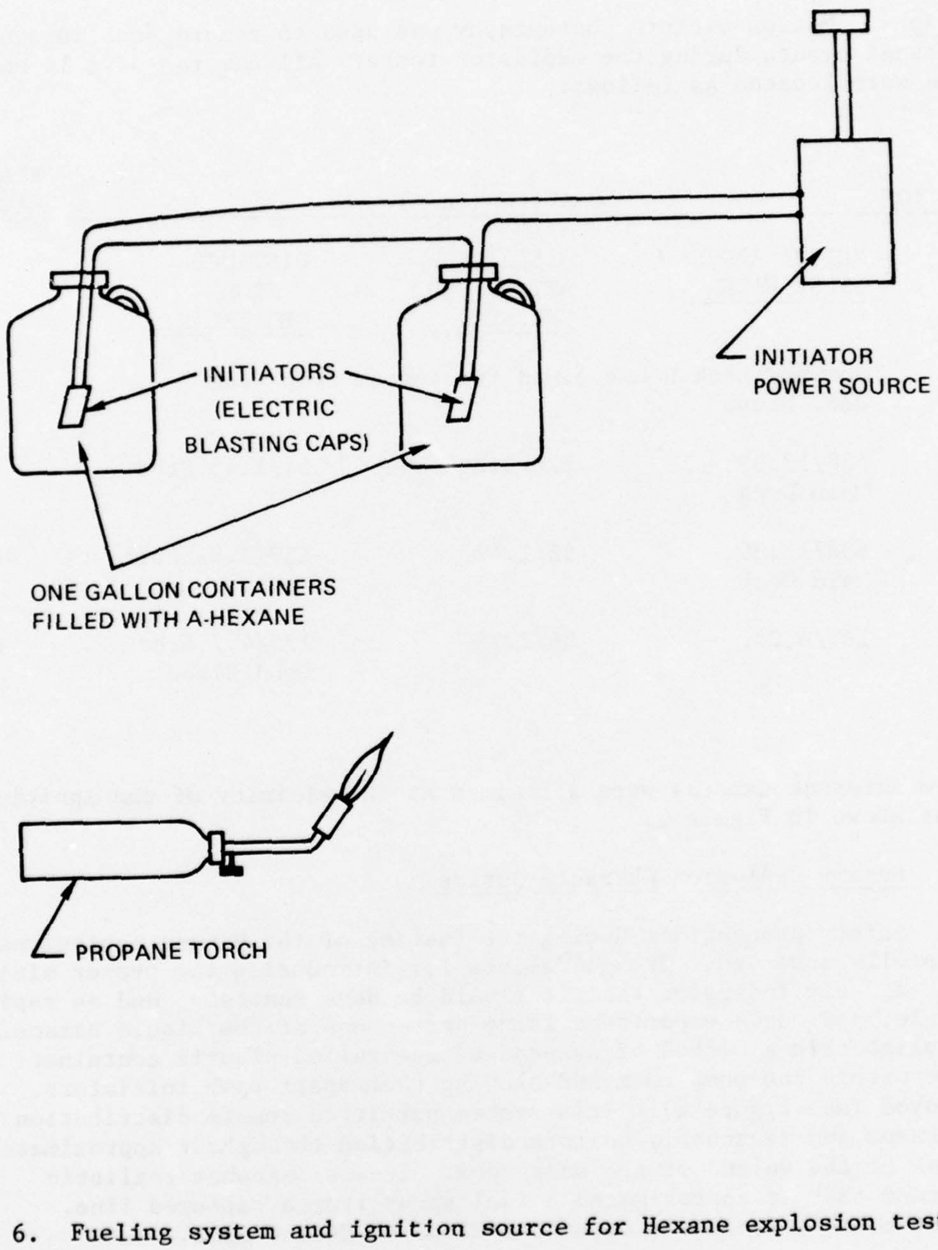


FIGURE 6. Fueling system and ignition source for Hexane explosion tests

initiators were wired internally to blow the container apart and the test was conducted in the open during calm wind conditions. The results of these tests are shown in Figure 7. For the first 95 milliseconds the mist traveled at approximately 73 feet per second (22.3m/sec). After 102 milliseconds its velocity slowed rapidly to zero as shown by the dashed line in Figure 7.

A series of unsuppressed tests (U1 through U12) were conducted (see Table 1) to systematically evaluate the effects of fuel quantity, fuel location, ignition source location, the number of igniters, and explosion venting. The hexane used in these tests was n-Hexane. It had the following characteristics: formula $CH_3\ (CH_2)_4\ CH_3$; molecular weight 86.17; flash point -7°F (-21°C); and specific gravity at 20°C 0.659. These tests led to the standardization of parameters shown in Table 2 to be used for the suppression attempt, Test S1, and the final unsuppressed test, U28. The unsuppressed explosions produced the pressure rise and maximum pressures indicated in Figure 8. It should be noted that the pressure rise was much more rapid than that expected from previous small-scale testing. Thus, in spite of the limitation of uncontrolled premixing of the Hexane vapor and air, a substantial explosion was obtained as evidenced by the maximum pressures during U28.

It should be noted that there was considerable variation in the time from ignition to the time when the pressure reached 1/2 psig (0.035 Kg/cm^2) as shown in Table 1. It is this time that is available for the detection of the explosion and actuation of the suppression system in order to produce a successful suppression. During the Hexane testing it was felt that the faster than expected pressure rise and the sharp "knee" in the transition from zero pressure rise to maximum pressure rise was due to turbulence. It was theorized that this turbulence was caused by the method used for fueling. Thus it was decided to try propane as a fuel in an attempt to develop a fueling technique which would minimize this turbulence.

2.4 Propane Explosion Characteristics

Zabetakis[7] shows that when a deflagration occurs in spherical enclosure of volume V with central ignition the approximate pressure rise ΔP at any instance after ignition is: $\Delta P \propto Kt^3/V$. He also found that the minimum elapsed time (t in milliseconds) required to reach the maximum pressure appears to be about $75\sqrt[3]{V}$ for the paraffin hydrocarbons and fuel blends such as gasoline (where V is in cubic feet). Thus for a stoichiometric mixture of propane in 100 percent of the pump room on the M/V RHODE ISLAND a pressure rise similar to that shown in Figure 5 with the maximum pressure occurring at approximately 2.0 seconds after ignition was expected. A stoichiometric mixture of propane in 10 percent of this volume was expected to give a pressure curve similar to the full explosion up to approximately 10 psig (0.703 Kg/cm^2) with the maximum pressure reaching approximately 12 psig (0.844 Kg/cm^2) at 0.9 seconds after ignition. These curves assume spherical flame propagation, ideal gases and unobstructed spherical test volumes.

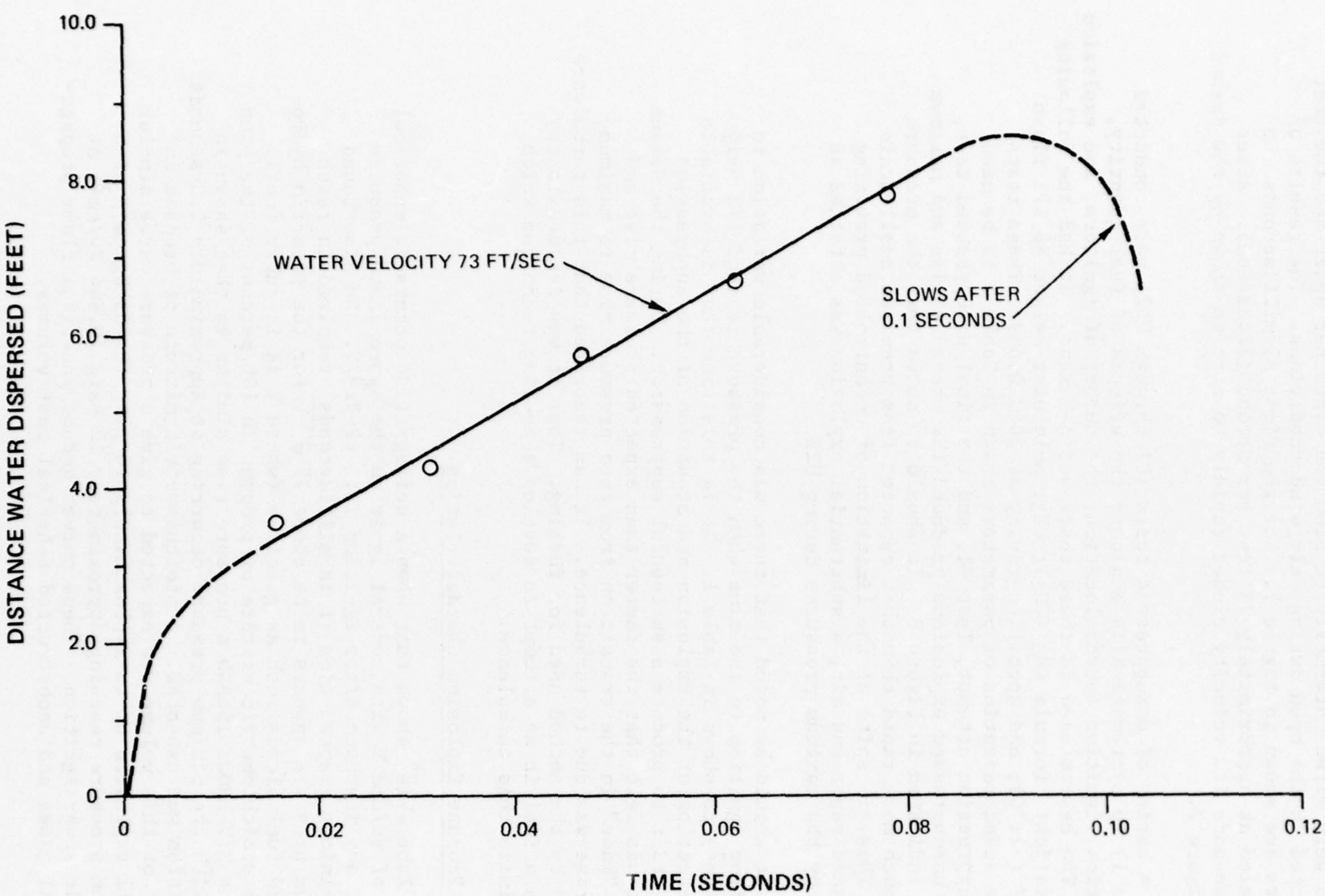


FIGURE 7. Water Dispersion test from one gallon bottle using 3 initiators (specific gravity of water = 1.0, of Hexane = 0.7)

TABLE 1 - PRINCIPAL CHARACTERISTICS OF UNSUPPRESSED HEXANE EXPLOSION TESTS U1-12, AND U28

n - HEXANE TEST FUEL

TEST NUMBER	TOTAL QUANTITY (Fl O_3)	NUMBER OF CONTAINERS	LOCATION (INCHES) HEIGHT ABOVE BILGE	AFT OF FWD BULKHEAD	FROM CENTER LINE	VENTILATION DOOR (12 ft^2)	HATCH (24 ft^2)	MAXIMUM PRESSURE (psig)	TIME TO MAXIMUM PRESSURE (sec)
U1	10	1	ON DECK			NA		NA	NA
U2	8	1	230	74	27 PORT	OPEN	OPEN	NO RECORDING	
U3	8	1	230	74	27 PORT	OPEN	OPEN	NO RECORDING	
U4	8	1	230	74	27 PORT	OPEN	OPEN	<0.25	-
U5	16	1	230	74	27 PORT	OPEN	OPEN	<0.25	-
U6	32	1	230	61	37 PORT	OPEN	OPEN	<0.25	-
U7	128	1	254	101	41 STBD	OPEN	OPEN	<0.25	
U8	256	1	254	101	41 STBD	CLOSED	OPEN	2.4	0.46
		1	254	115	66 PORT				
U9	192	1	254	101	41 STBD	CLOSED	OPEN	1.2	0.53
		1	254	115	66 PORT				
U10	320	1	254	101	41 STBD	CLOSED	OPEN	3.6	0.43
		1	254	115	60 PORT				
		1	254	74	34 PORT				
U11	384	1	210	101	41 STBD	CLOSED	OPEN	4.3	0.53
		1	210	115	60 PORT				
		1	248	62	34 PORT				
U12	384	1	210	101	41 STBD	CLOSED	OPEN	6.1	0.39
		1	210	115	60 PORT				
		1	248	62	34 PORT				
U28	768	6	AS LISTED IN TABLE 2			OPEN	OPEN	12.8	0.53

IGNITION SOURCE LOCATIONS

TESTS U1 - U10	230	89	14 PORT
TESTS U11, U12, AND U28	185	89	14 PORT

TABLE 2

STANDARDIZATION OF INDEPENDENT VARIABLES FOR SUPPRESSION TESTS OF n - HEXANE EXPLOSIONS

FUEL: 6 ± 0.1 Gallons n - Hexane

IGNITION SOURCE: Propane Flame Igniter

TEST VOLUME: (Based on Bilge Water 72" Below Lowest Catwalk and Excluding Deck House Volume.)
19,150 ± 10 ft^3

VENTING: Both Door and Hatch Open

LOCATIONS (IN):

	HEIGHT ABOVE BILGE WATER	DISTANCE AFT OF FWD BULKHEAD	DISTANCE FROM CENTERLINE
IGNITION SOURCE	185	89	14 to PORT
FUEL CONTAINERS			
A	241	57	14 to PORT
B	241	121	39 to STBD
C	154	57	39 to STBD
D	136	121	14 to PORT
E	154	57	62 to PORT
F	241	121	62 to PORT

DETECTION: Pressure Detectors set for 1/2 PSIG

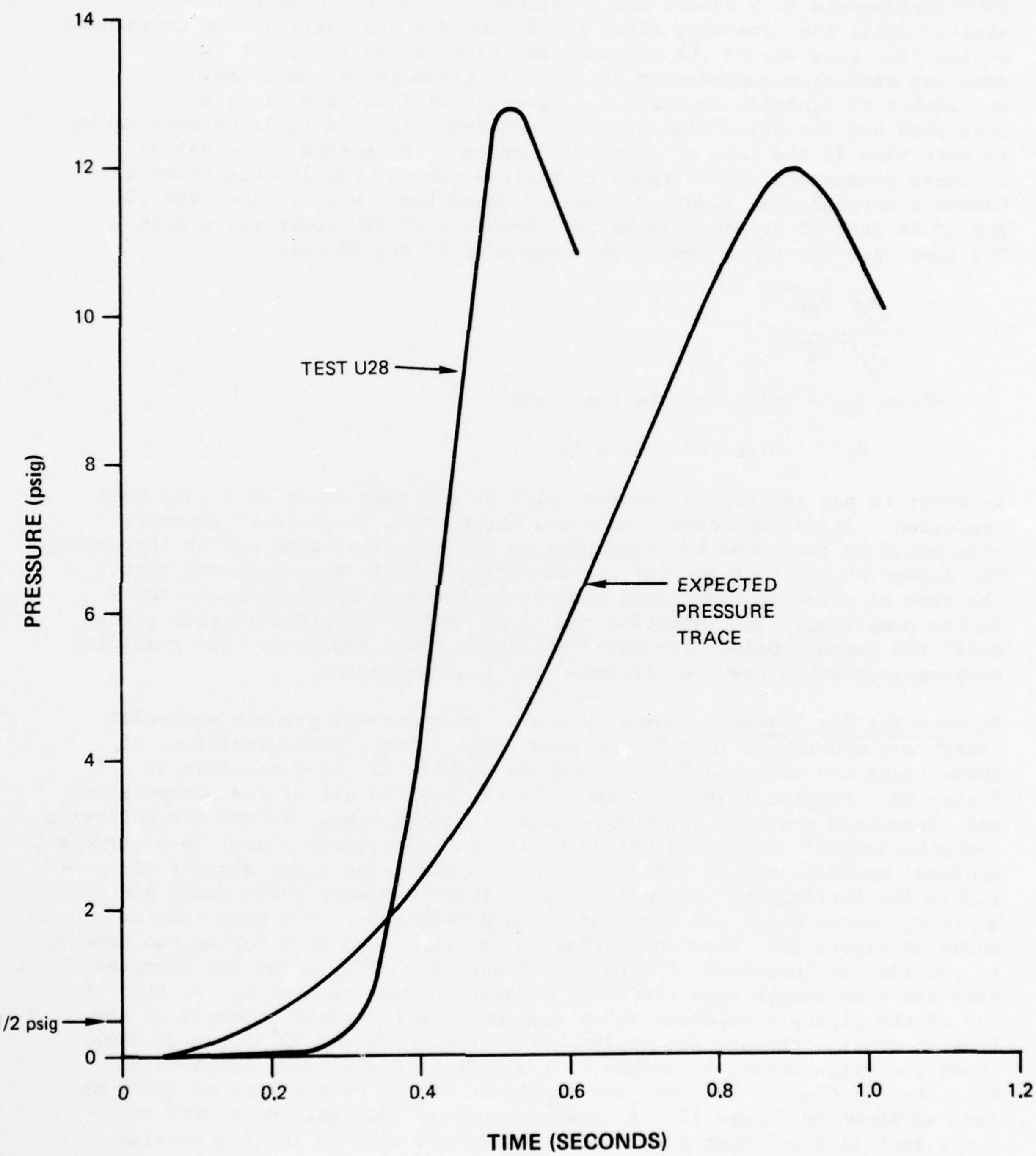


FIGURE 8. Pressure-time trace for Test U28 as compared to the expected trace

Silo Tests - To further check these predictions, Fenwal conducted a series of propane air explosions in a 381 cubic foot ($10.8 m^3$) cylindrical test silo having a radius of 2.66 feet (0.81 m). The shape of the test vessel will have an effect on the rate of pressure development[7,9]. The developments in a sphere and a cylinder of equal radius will be similar until the advancing flame fronts contact the shell of the containers By the time this occurs the pressure has risen above the point that concerns explosion suppression design. In these tests the location and number of ignition sources, the location of fuel injection, the vent area and the delay time between fuel injection and ignition were varied to determine if the rate of pressure rise could be varied. The values of these parameters can be found in Table 3 and the results are shown as Curves A through G in Figure 9. All of these tests were fueled with 200 gms (0.44 lbs) of propane discharged through a TF12FC corkscrew nozzle. The time base for these curves were expanded by the factor:

$$\frac{\sqrt[3]{V_{pr}}}{\sqrt[3]{V_s}}$$

where V_{pr} = volume of the pump room

V_s = volume of test silo

in order to put the curves theoretically on the same scale as a pump room explosion. It was apparent from these curves that the rate of pressure rise could be increased by permitting an optimum delay time and by increasing the number of ignition sources. From these tests it was concluded that the rate of pressure rise could also be tailored in the full-scale tests in the pump room. The intention was to so tailor the pressure/time traces until the curve labeled "expected" in Figure 9 was produced. The remaining suppressions would then be attempted for this explosion.

Propane Fueling System - Thus a series of unsuppressed propane explosion tests were undertaken in the pump room. The primary characteristics of these tests are shown in Table 4 and the results of the explosions in Figure 10. Propane (C_3H_8) was used for the fuel in all of the unsuppressed and suppressed tests except where Hexane is designated. It had the following characteristics: molecular weight 44.10; purity (liquid phase) 96.0 percent minimum; specific volume 8.5 cubic feet per pound and vapor density of 1.56. The fueling system consisted of a fuel reservoir above decks and a piping system which ran down the forward bulkhead of the pump room as shown in Figure 11. Near the bottom of the pump room this piping was branched to provide two locations of fuel injection. Each leg in the two branches were the same length thus providing a balanced fueling system. At the top of the piping a solenoid valve was employed for remote control of the flow of propane through the piping. The propane exited 92 inches (2.34m) above the bilge water, 46 inches (1.17m) aft of the forward bulkhead and 40 inches (1.02m) to the port and starboard of the center line of the pump room as shown in Figure 12. A corkscrew nozzle (designated TF20FC) and a 1/2 inch (1.27cm) open pipe were experimented with as fueling nozzles. The corkscrew nozzle was intended to increase vapor dispersion. The type of nozzle did not seem to have a significant effect (see Table 4) and so the 1/2 inch (1.27cm) open pipe was used throughout all remaining propane tests.

TABLE 3 - CHARACTERISTICS OF PROPANE EXPLOSIONS IN 381 FT^3 SILO

TEST DESIGN	IGNITION SOURCE LOCATION ON CTR. LINE FROM BOTTOM (INCHES)	HEIGHT OF FUEL INJECTION POINT ON CTR. LINE POINTED DOWN (INCHES)	VENTING AREA (FT^2)	DELAY TIME (SEC)
A	12	9	3.7	45
B	12	9	3.7	45
C	12	9	3.7	45
D	15	30	5.6	25
E	30-12 OFF CTR. LINE 30-12 OFF CTR. LINE	30	5.6	25
F	15-12 OFF CTR. LINE 15-12 OFF CTR. LINE	30	5.6	25
G	15	30	3.7	25

TABLE 4 - PRINCIPAL CHARACTERISTICS OF UNSUPPRESSED PROPANE EXPLOSION TESTS U13-U27, AND U29-U31

TEST NUMBER	TOTAL QUANTITY (LBS) ± 1/4	PROPANE TEST FUEL FUELING LOCATION (INCHES) HEIGHT ABOVE BILGE	AFT OF FWD BULKHEAD	FROM CENTER LINE	IGNITION SOURCE (LOCATION DESCRIBED IN TEXT)	TIME FROM FUEL INJECTION TO IGNITION (SEC) ± 2.0	MAXIMUM PRESSURE (PSIG) ± 0.1	TIME TO MAXIMUM PRESSURE (SEC) ± 0.003	
U13	3	41	46	ON CNT.LINE	SPARK IGNITER	30	FUEL PIPE RUPTURED NO EXPLOSION		
U14	3					15	2.2	-	
U15	5					15	4.0	0.605	
U16	8	41	46	ON CNT.LINE		20+15*	4.2	0.361	*DID NOT FIRE ON INITIAL SPARK
U17	8	2(42 (42	46 46	40 PORT 40 STBD		30	5.5	0.317	
U18	10	2(42 (42	46 46	40 PORT 40 STBD		40	4.5	0.475	
U19	10	2(68 (68	46 46	40 PORT 40 STBD		30	8.7	0.192	
U20	10					30	8.2	0.255	HATCH & DOOR CLOSED
U21	10					30	7.9	0.268	
U22	10					60	6.0	0.560	
U23	10	2(68 (68	46 46	40 PORT 40 STBD		90	5.7	0.327	
U24	10	2(92 (92	46 46	40 PORT 40 STBD		60	10.3	0.353	
U25	12					60+20*	10.4	0.436	*DID NOT FIRE ON INITIAL SPARK
U26	12					80	9.6	0.442	
U27	12	2(92 (92	46 46	40 PORT 40 STBD		60	7.6	0.573	
U29	10	2(164 (164	46 46	40 PORT 40 STBD		60	1.3	1.4 ± 0.01	BILGE WATER LEVEL RAISED SIX FEET
U30	12	2(164 (164	46 46	40 PORT 40 STBD	SPARK IGNITER	60	3.4	1.1 ± 0.01	
U31	12	2(92 (92	46 46	40 PORT 40 STBD	HOT WIRE IGNITER	60	12.0	0.221	

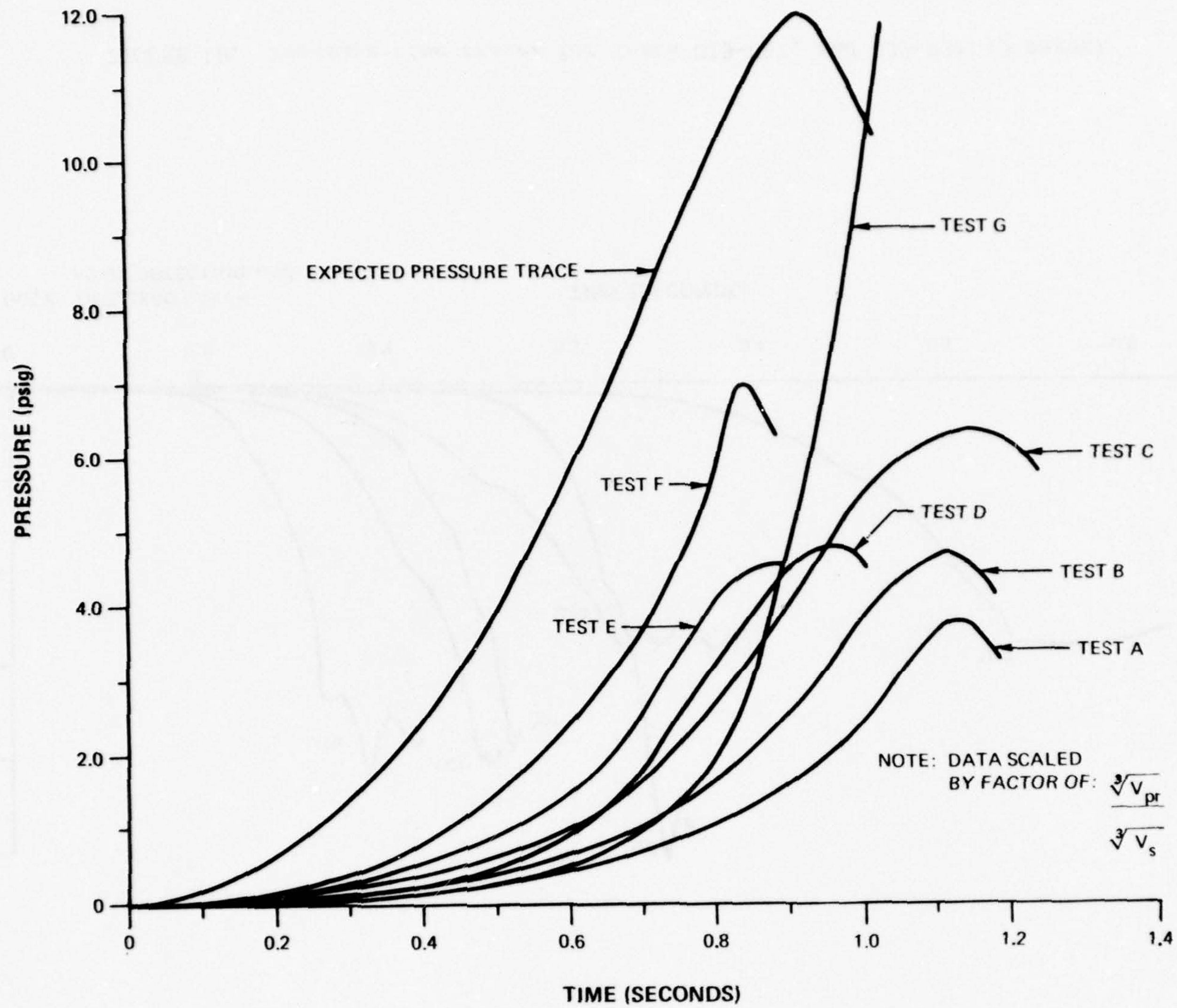


FIGURE 9. Pressure-time traces from preliminary silo tests

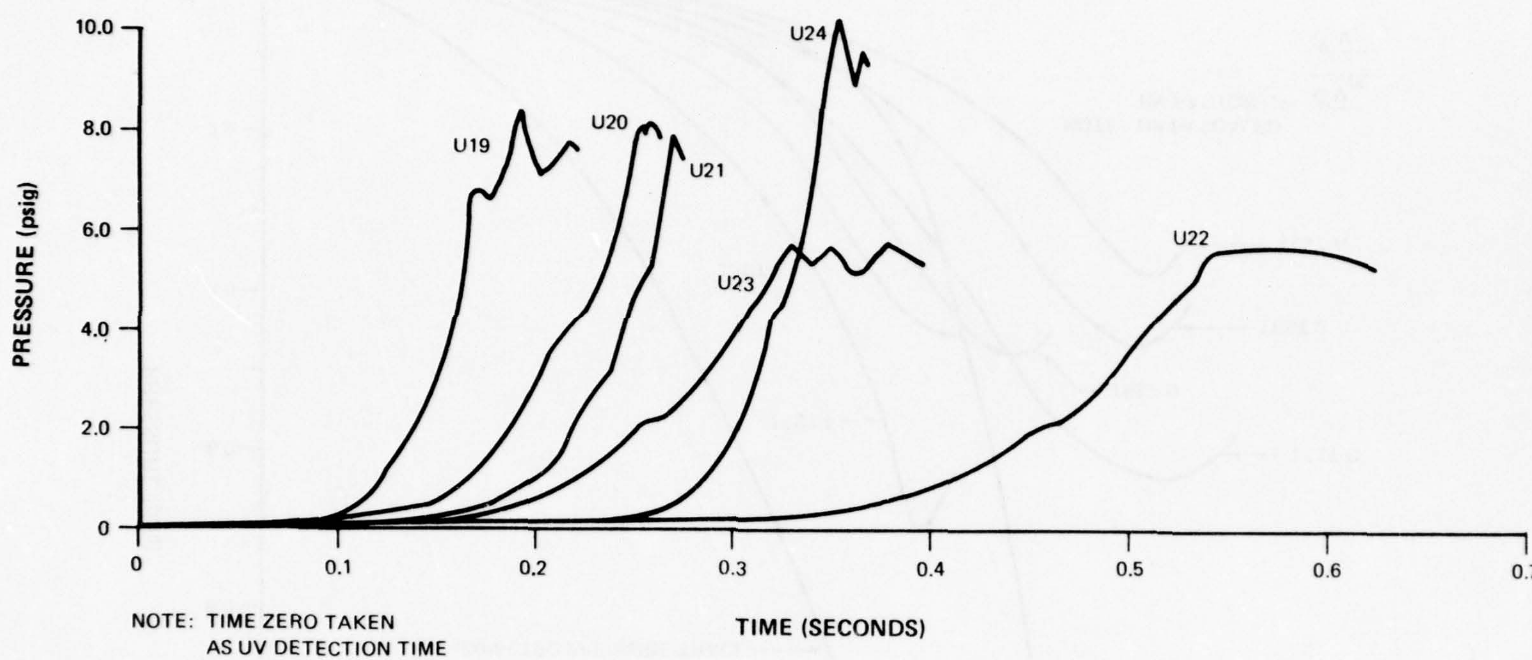
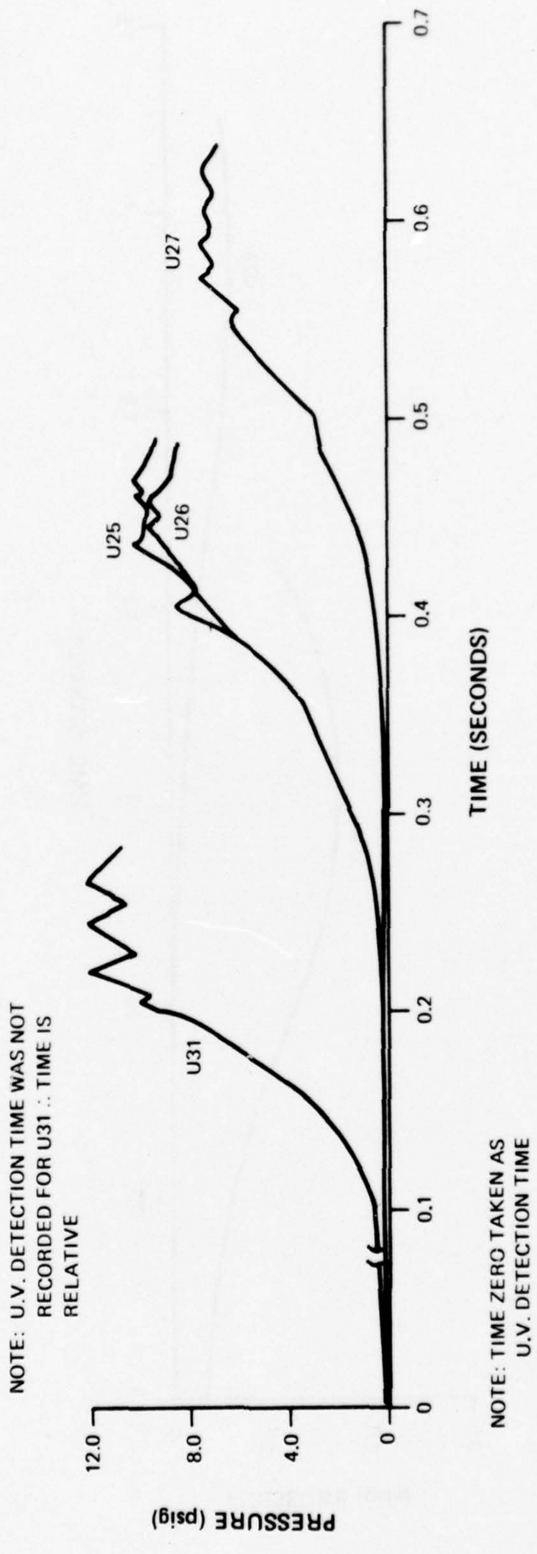
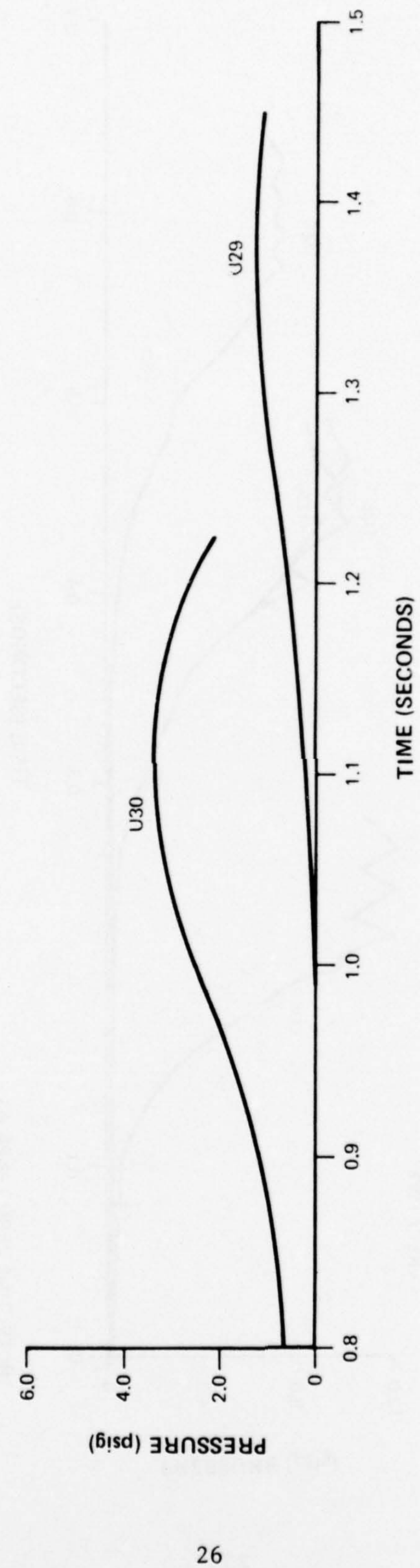


FIGURE 10. Pressure-time traces for Tests U19-U27, and U29-U31 (3 pages)


NOTE: U.V. DETECTION TIME WAS NOT RECORDED FOR U31 ∴ TIME IS RELATIVE
NOTE: TIME ZERO TAKEN AS U.V. DETECTION TIME
PRESSURE (psig)
12.0
8.0
4.0
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TIME (SECONDS)
U31
U25
U26
U27



PRESSURE (psig)
6.0
4.0
2.0
0
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
TIME (SECONDS)
U30
U29

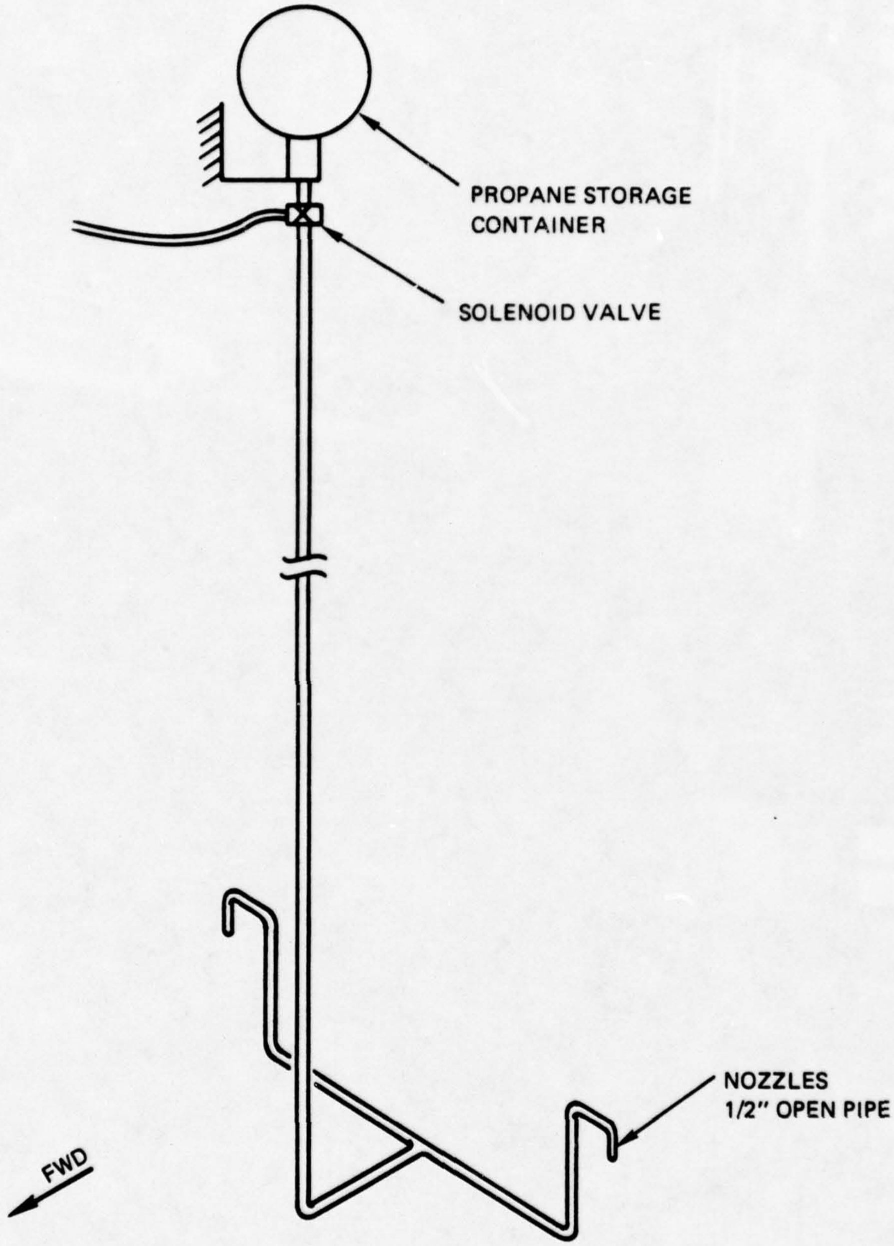


FIGURE 11. Propane fueling system (schematic)

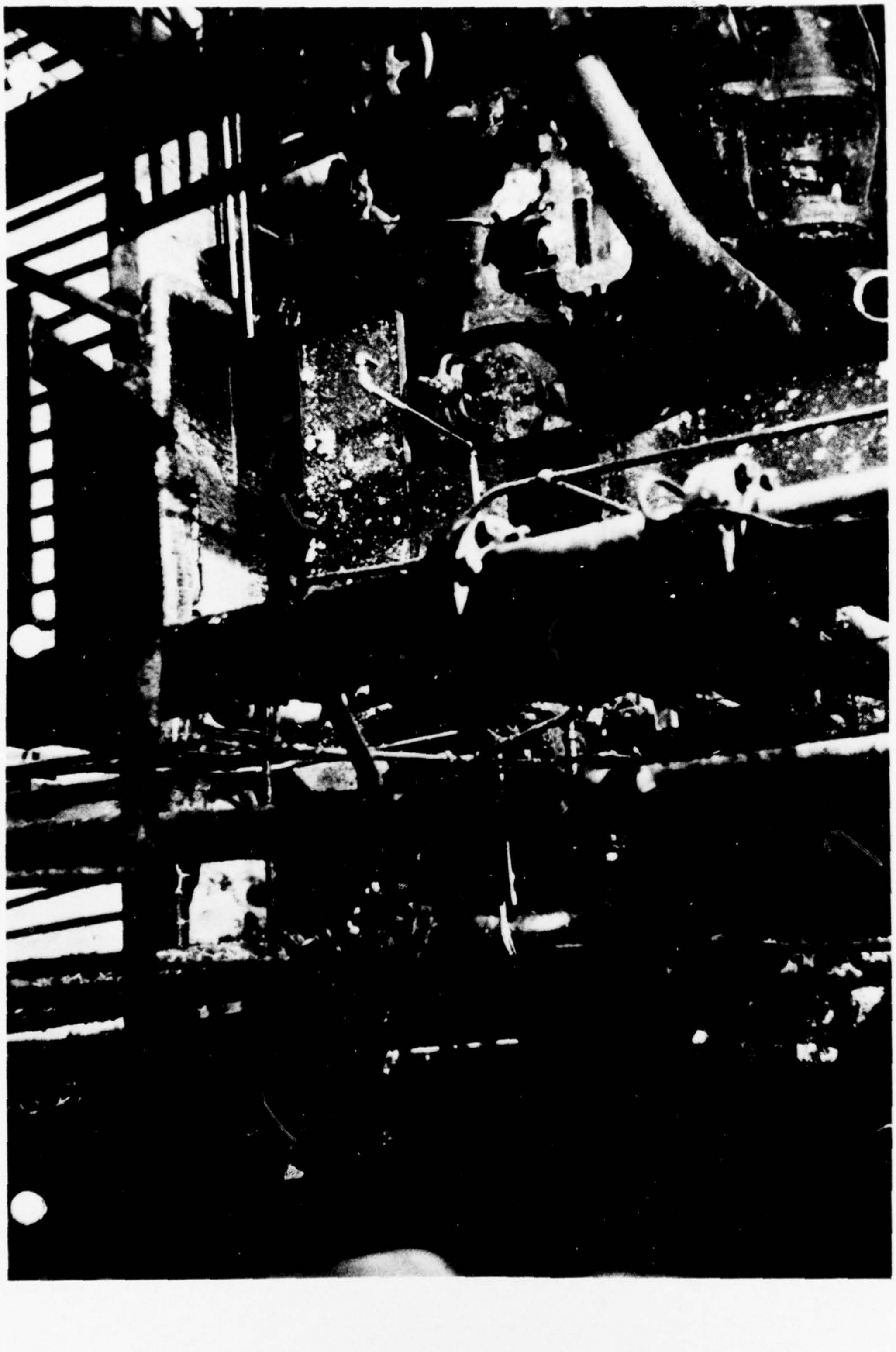


FIGURE 12. Propane fueling system as installed

Delay Time - Because of the turbulence created with the Hexane fueling system and the results of the silo tests it was decided to provide a delay time between propane injection and ignition. This delay time would permit the propane gas to come to a quiescent state and thus the turbulent fueling problem would be eliminated. During the unsuppressed tests, U13 through U26, it was found that a 60-second delay time produced the maximum pressure for a given fuel loading. In some instances such as test U25 when ignition was attempted at the end of the 60-second delay time, an explosion did not result presumably because the fuel air mixture was too rich in the vicinity of the ignition source. In these cases an added delay time was allowed to obtain a successful ignition. During the propane explosions involving a fuel load of 12 pounds,(5.44 Kg), it was found that the fuel discharge time was 16 ± 1 seconds.

The spark igniter and hot wire igniter were used during the unsuppressed and suppressed propane explosions. The spark igniter was located 12 inches (0.30m) above the bilge water, 78 inches (1.98m) aft of the forward bulkhead and 30 inches (0.76m) port of the center line as shown in Figure 13. The hot wire igniter was located 28 inches (0.71m) above the bilge water, 89 inches (2.26m) aft of the forward bulkhead and 27 inches (0.69m) starboard of the center line as shown in Figure 14.

Flooded Bilge Tests - It was apparent from Tests U25-U27 and U31 that the rate of pressure rise was much more rapid than had been predicted. In fact, the lower portion of the pressure time curve was surprisingly consistent from one test to another in spite of the variation in ignition source location, fueling locations and fuel nozzle geometry. However, in Tests U29 and U30 where the majority of the obstructions in the lower portion of the pump room were removed by flooding (leaving a 15,000 cubic foot ($425m^3$) internal volume) as shown in Figure 15 the drastic reduction in pressure rise and maximum pressure should be noticed. During these tests the geometry of the fueling system, its location and the location of the ignition source were all raised the same amount as the bilge water. Thus the major independent variable which was changed for these two tests was the quantity of obstructions in the pump room.

In spite of the limitation of uncontrolled premixing of the propane and air, a good explosion was obtained as evidenced by the maximum pressures developed and the flame colors observed. In fact, it can be inferred that the fuel air mixture was reasonably close to stoichiometric in approximately 10 percent of the volume of the pump room for the tests using 12 pounds (5.44 Kg) of propane. Supporting evidence for this is that the pressure obtained in tests U25 to U27 and U31 approached the 12 psig (0.84 Kg/cm^2) expected and that the color of the flame front was a bluish to bluish white which, as can be seen in Figure 16, indicates a mixture slightly leaner than stoichiometric[10,22]. Again the time from ignition to the time when the pressure reached the 1/2 psig (0.035 Kg/cm^2) point should be noted.

Pressure Detection Limitations - The testing program was initially set up to employ high speed pressure and temperature detectors to sense the explosion and activate the explosion suppression systems. It became apparent very early in the testing program that the high speed temperature detectors were not fast enough for timely detection. The high speed pressure transducers were diaphragm type devices capable of closing the detection circuit at

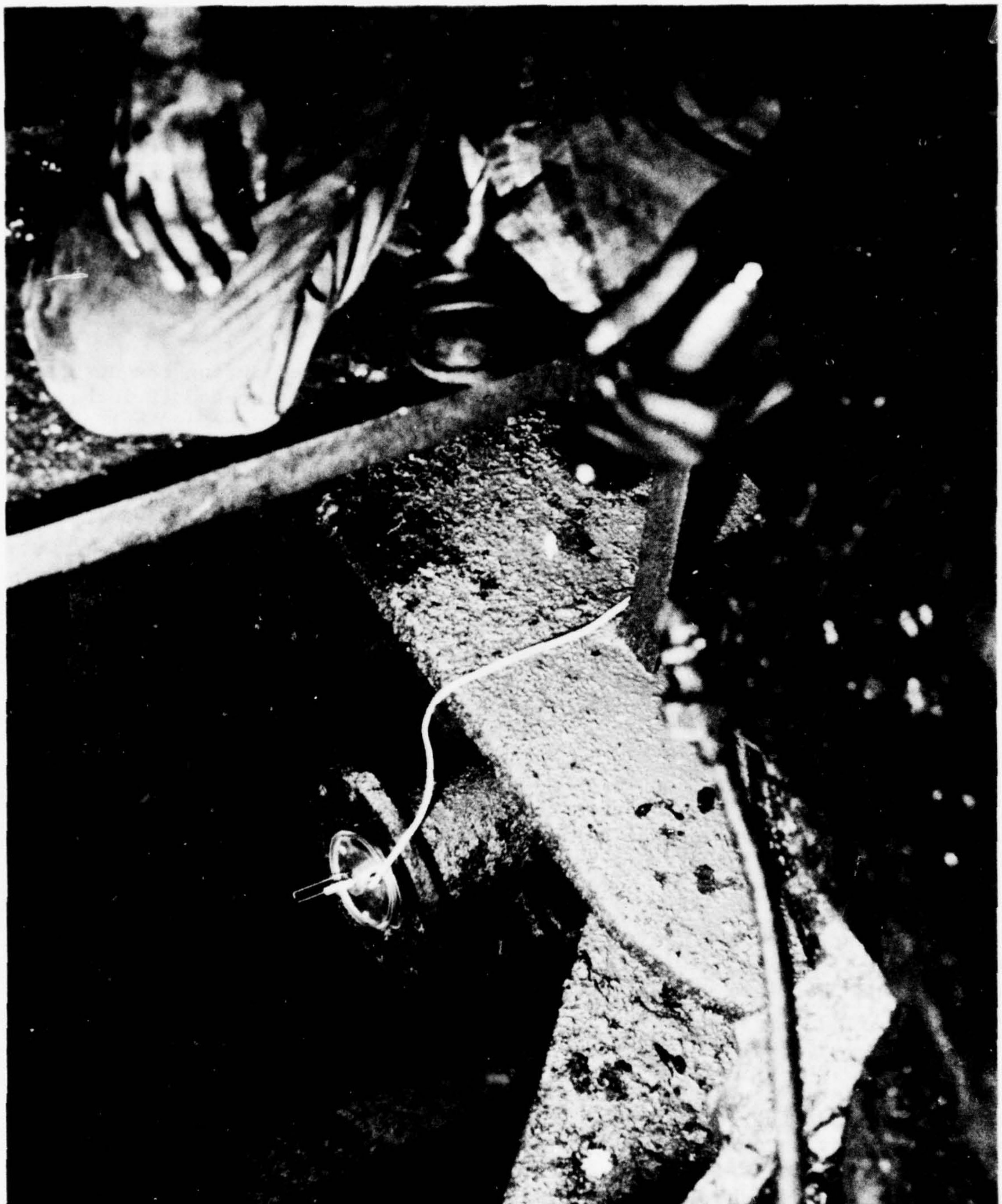


FIGURE 13. Spark igniter

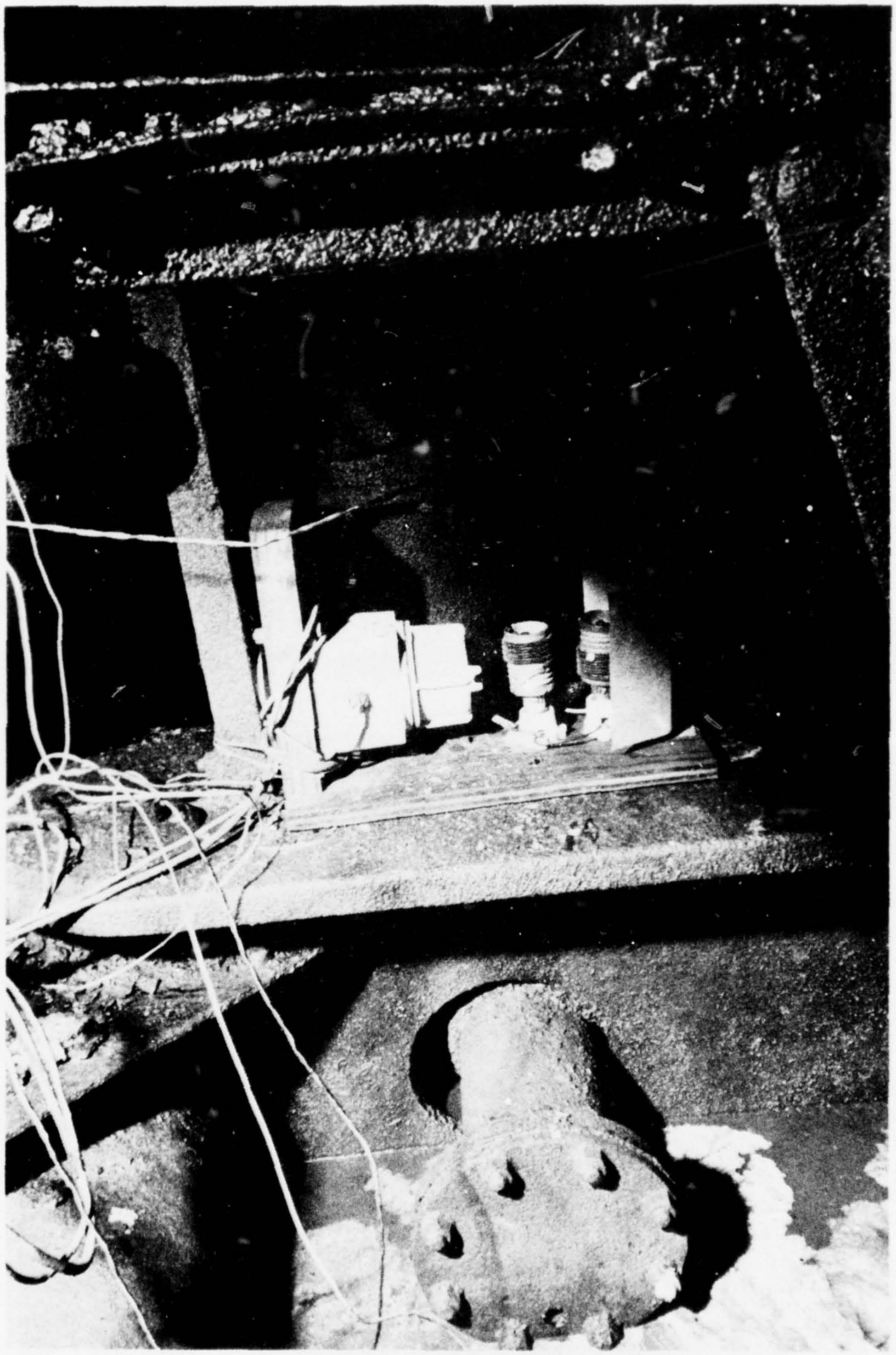


FIGURE 14. Hot wire igniter

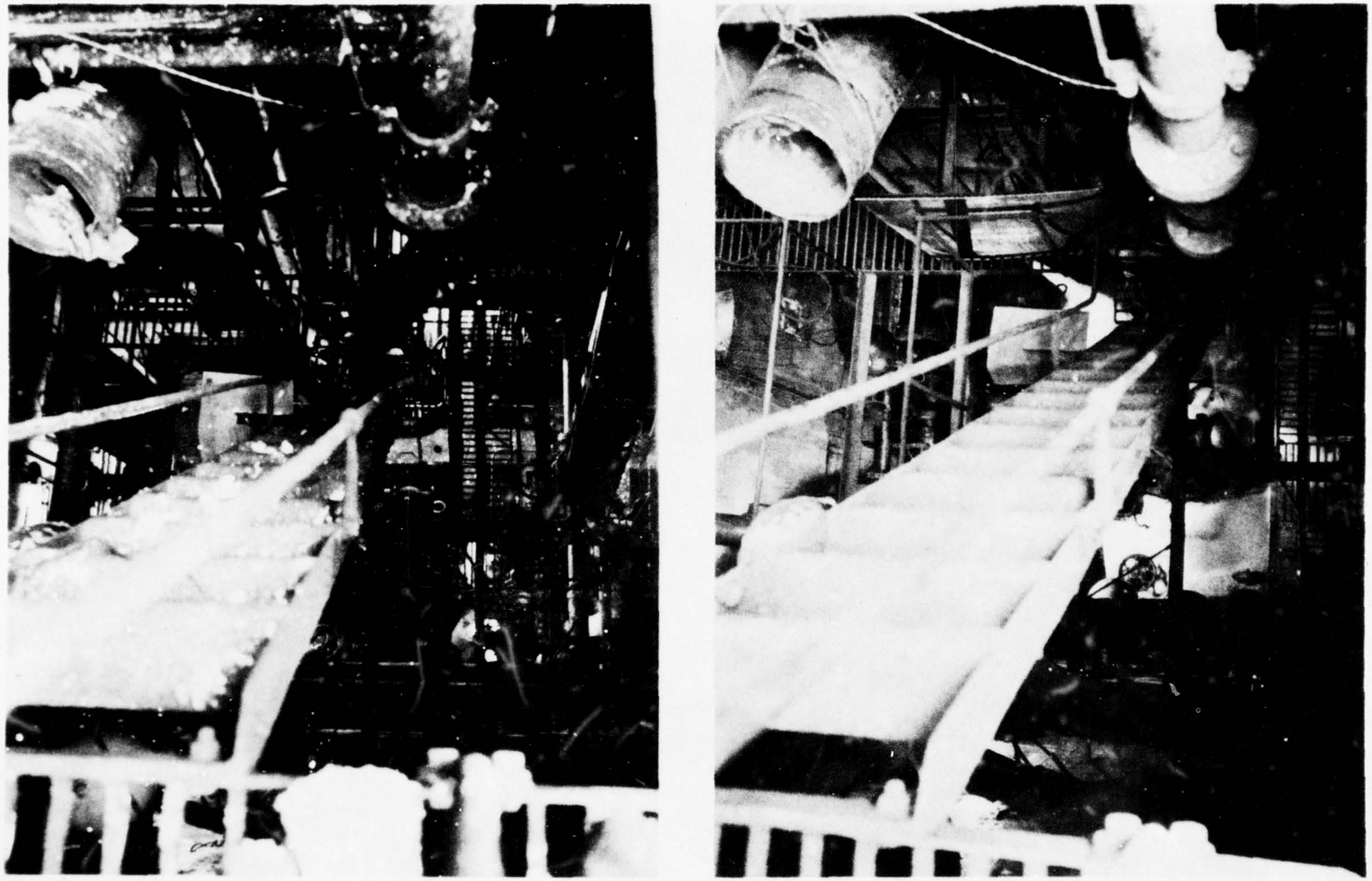


FIGURE 15. Views of pump room from top before and after flooding

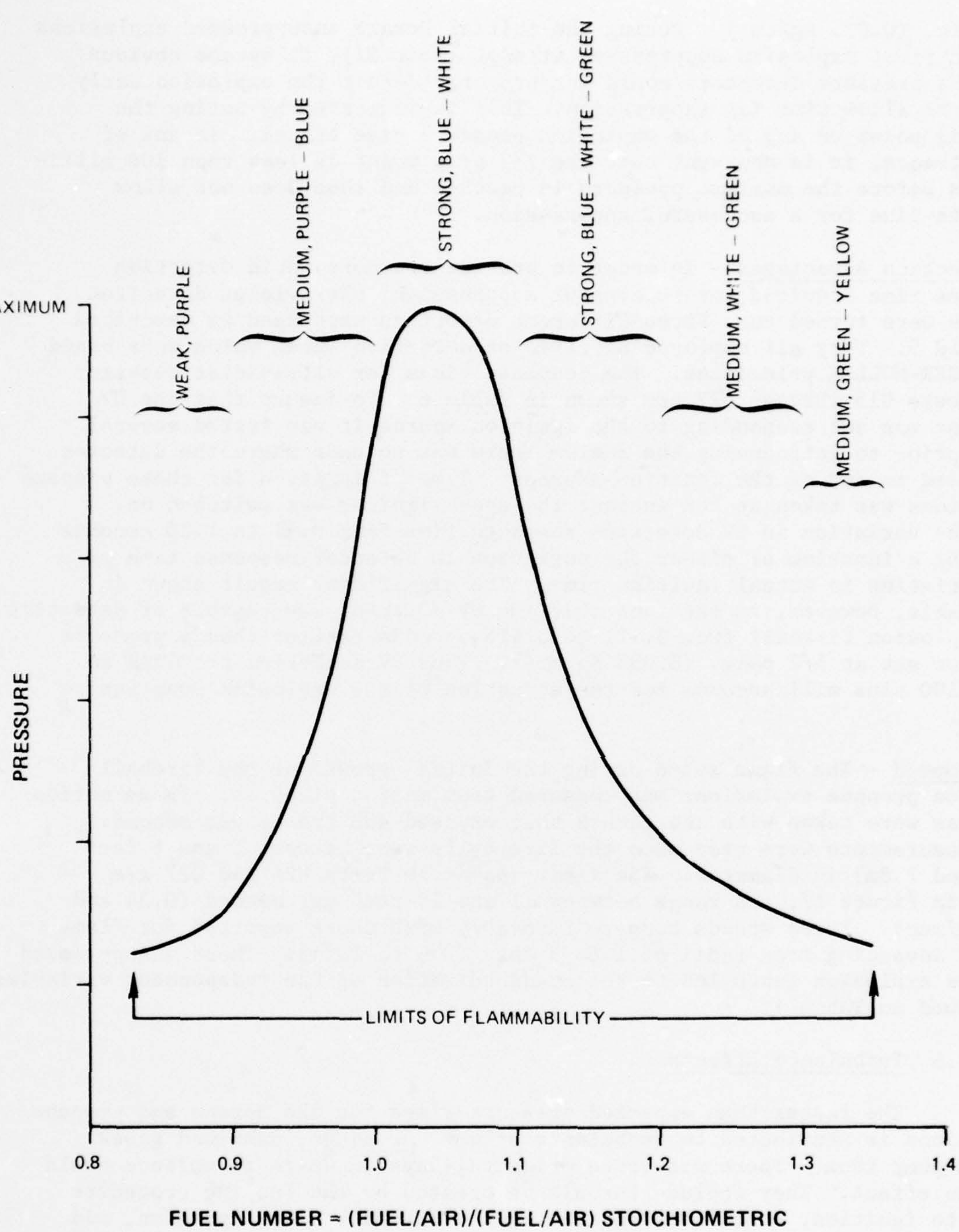


FIGURE 16. Flame color and intensity as a function of fuel number for premixed hydrocarbon-air flames

1/2 psig. (0.035 Kg/cm^2). During the initial Hexane unsuppressed explosions and the first explosion suppression attempt (Test S1), it became obvious that the pressure detectors could not properly detect the explosion early enough to allow time for suppression. This is indicated by noting the 1/2 psig point on any of the explosion pressure rise traces. In any of these traces, it is apparent that the 1/2 psig point is less than 100 milliseconds before the maximum pressure is reached and thus does not allow adequate time for a successful suppression.

UV Detection Advantages - In order to provide the more rapid detection response time required for successful suppression, ultraviolet detection systems were turned to. Three different detectors were used as described in Table 5. They all employed ultraviolet detection tubes which were based on GEIGER-MULLER principles. The response times for ultraviolet detector B in Tests U15 through U27 are shown in Table 6. To insure that the UV detector was not responding to the ignition source it was tested several times prior to introducing the fuel. There was no case where the detector responded to any of the ignition sources. Time of ignition for these paopane explosions was taken at the instant the spark igniter was switched on. Thus the variation in UV detection response time from 0.37 to 1.20 seconds could be a function of either the variation in detector response time or the variation in actual ignition time. The significant result shown in this table, however, is the fact that the UV detector was capable of detecting the explosion fireball from 0.111 to 0.415 seconds earlier than a pressure detector set at 1/2 psig. (0.035 Kg/cm^2). Thus UV detection provides an extra 100 plus milliseconds for the actuation of the explosion suppression system.

Flame Speed - The flame speed during the initial growth of the fireball in these propane explosions was measured from motion pictures. These motion pictures were taken with the camera that exposed 488 frames per second. The measurements were made when the fire balls were between 1 and 6 feet (0.3 and 1.8m) in diameter. The flame speeds in Tests U26 and U27 are shown in Figure 17, and range between 11 and 12 feet per second (0.34 and 0.37 m/sec). These speeds compare favorably with those reported for flame fronts advancing from radii of 1 to 5 feet (0.3 to 1.5m). These unsuppressed propane explosion tests led to the standardization of the independent variables described in Table 7.

2.5 Turbulence Effects

The faster than expected pressure rises for the Hexane and propane explosions is attributed to turbulence of the burned and unburned gases in the pump room. There are three principal ways in which turbulence could have an effect. They include turbulence created by the fueling procedure prior to ignition, turbulence created by the fireball after ignition, and turbulence created by obstructions to the growth of the fireball.

If the fuel were being transported rapidly, at the time of ignition, then its velocity would increase the flame speed and thus produce a more rapidly expanding fireball and an associated increase in the rate of pressure rise. This is not believed to be a major factor in the rate of pressure rise in this test series. The supporting evidence is that the propane was in a quiescent state when it was ignited and yet still produced a more

TABLE 5

GEIGER-MULLER ULTRA VIOLET EXPLOSION
DETECTORS (TUBE & AMPLIFIER) CHARACTERISTICS

	UV DETECTORS		
	A	B	C
Total Response Time (sec) (12" sq. Pan, 100 Octane Gas, @ 15)	0.060	0.010	0.010
Relay Closure Time (sec)	0.001	0.010	<0.001
Spectral Response			
Range (Angstroms)	1700-2600	1850-2450	Same as B
Peak (Angstroms)	2150±50	2150±30	Same as B
Cone of Vision	90^{o}	90^{o}	Same as B
Electrode Design			
Cathode	Hemi Sphere	Solid Flat Plate	Same as B
Anode	Wire	Perforated Plate	

TABLE 6

RESPONSE TIMES FOR UV DETECTOR B TO UNSUPPRESSED PROPANE EXPLOSIONS

TEST NUMBER	TIME FROM IGNITION TO UV DETECTION (SEC)	TIME FROM UV DETECTION TO ½ PSIG (SEC)
U15	0.39	0.141
U16	0.98	0.222
U17	0.46	0.180
U18	0.74	0.318
U19	0.48	0.111
U20	0.60	0.150
U21	0.71	0.186
U22	0.75	0.380
U23	0.37	0.190
U24	0.55	0.262
U25	1.00*	0.296
U26	0.73**	0.346
U27	1.20***	0.415

*UV Detector A responded 0.01 sec. later

**UV Detector A responded 0.05 sec. later

***UV Detector A responded 0.01 sec. earlier

TABLE 7

STANDARDIZATION OF INDEPENDENT VARIABLES
FOR SUPPRESSION TESTS OF PROPANE EXPLOSIONS

FUEL:	12 ± ¼ lbs. Propane (Nat.)
FUELING SYSTEM:	Two ½" pipe nozzles as described
IGNITION METHOD:	Spark Igniter for Tests S-2 through S-10 Hot Wire for Test S-11 through S-14
VOLUME:	18120 ± 10 ft^3 (based on bilge water 52" below lowest catwalk and excluding deck house volume)
VENTING:	Both door and hatch open
DETECTION:	Ultra Violet based on GEIGER-MULLER principles

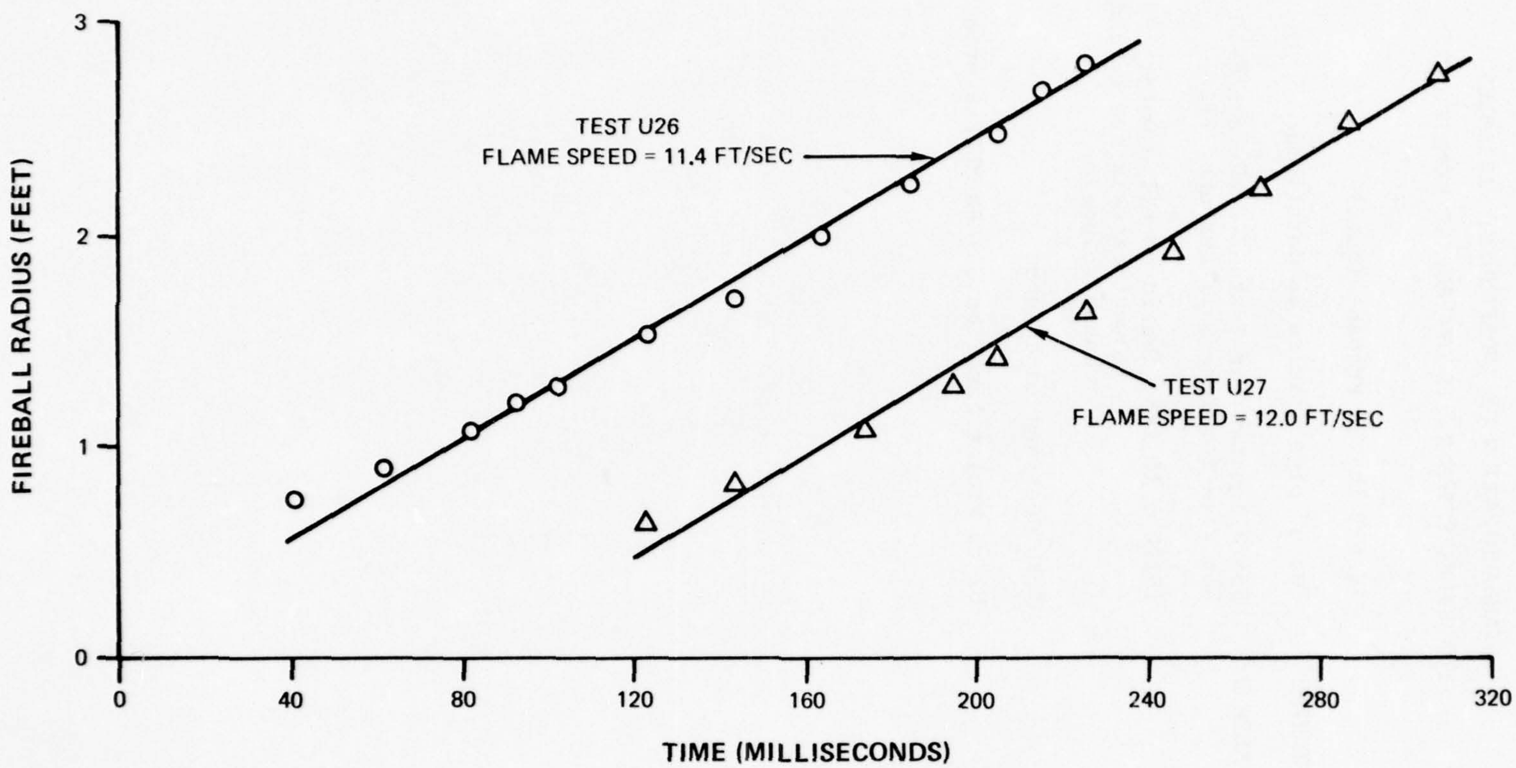


FIGURE 17. Flame speed for propane-air explosions measured with top/488 camera

rapid pressure rise than expected. Also the transport of Hexane would be very similar to that of water. The water dispersion test indicated limited to no motion after 100 milliseconds. Thus the Hexane transport due to the fueling procedure would have been very slow at the time of ignition.

A certain amount of turbulence can be created by the fireball drawing fuel and air into it as it is growing. This effect is not considered to be a major factor in these explosions except as it relates to obstructions because this same turbulence would be created in a test enclosure such as the silo, used during the preliminary tests. These preliminary silo tests (shown in Figure 9) did not indicate the rapid rate of pressure rise observed in the pump room tests. It is believed that the turbulence created by obstructions in the pump room is the primary reason for the increased rate of pressure rise. As the fireball draws fuel and air to it, the mixture is forced around obstructions and turbulence is increased. Furthermore, as the hot gases expand and are forced to flow through small areas created by obstructions, there is an increased flow rate which would tend to increase the flame speed of the fireball. This phenomenon is depicted in Figure 18 where each picture is separated by 20 milliseconds. Note that prior to the obstruction, the flame front is advancing at a reasonably constant rate but once it is forced through the restricted area, (lower right of each picture), its velocity increased dramatically. Finally evidence which supports the conclusion that obstructions created turbulence which in turn increased the rate of pressure rise is provided by tests U29 and U30. As noted in Section 2.4, the only difference between these tests and previous unsuppressed propane explosions was the fact that the majority of the obstructions in the lower portion of the pump room were removed. The rate of pressure rise and the maximum pressure for these tests was drastically reduced as shown in Figure 10. Thus it is concluded that obstructions to the growth of the fireball created a turbulence which in turn increases the rate of pressure rise in an explosion. This conclusion, of course, has a pronounced effect on the time available for detection and actuation of explosion suppression systems. It is felt, however, that it is a realistic phenomenon in large volume spaces on ships cluttered with machinery and, therefore, should be taken into consideration.

3.0 EXPLOSION SUPPRESSION SYSTEM A

An explosion suppression is a step-by-step process. Once an ignition has occurred and the incipient explosion is developing a sequence of events must follow. These include:

a. A detector recognizes the incipient explosion.

b. A signal from the detector actuates a control circuit which in turn fires initiators.

c. The initiators rupture a restraining diaphragm, causing the release of a suppressing agent.

d. The agent travels from the point of release to engulf the flame front.

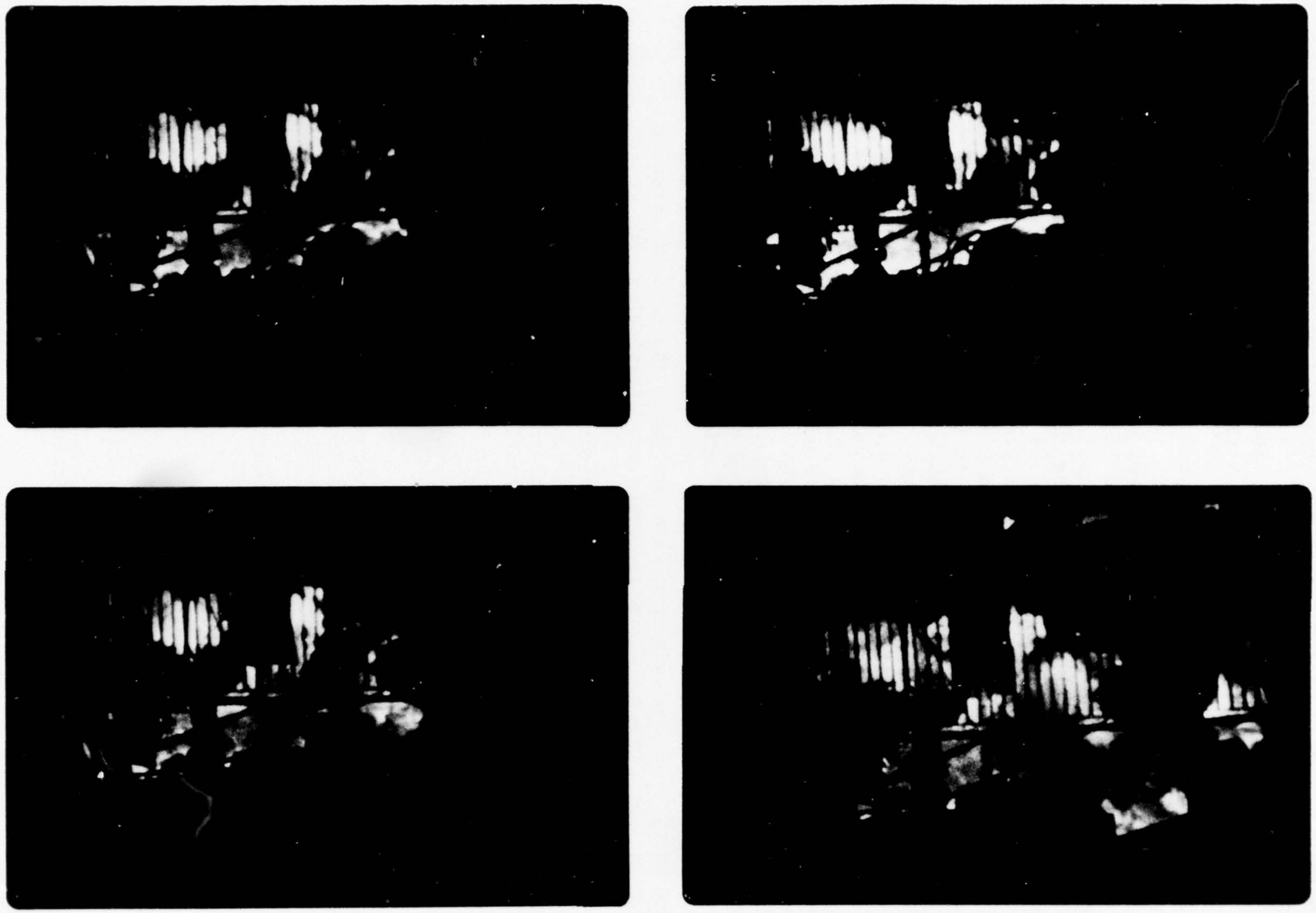


FIGURE 18. Turbulence in the fireball created by obstructions in the pump room (pictures separated by 20 milliseconds)

e. The flame is extinguished, the explosion has been suppressed.

Each of these steps has a finite time requirement. As the sequence is proceeding the flame front is expanding and its propagation velocity is increasing. Thus, a suppression represents a race against time. The successful suppression system must respond and overtake the growth of the explosion.

Explosion suppression system A was designed and fabricated from existing components. These components were normally used for explosion protection of volumes less than 1/10 that of the pump room. Thus the development problems were those of stretching the technology to a much larger system. The system was designed to protect the entire volume including the wings.

3.1 System Design

In finalizing the system design for the explosion suppression tests in the pump room of the M/V RHODE ISLAND, consideration was given to the detection system. The initial function of an explosion protection system is to sense an incipient explosion. Therefore, detection units must be extremely sensitive to the conditions indicating the onset of an explosion, but insensitive to normal variations which might occur within the hazard area being protected.

Detector - The initial system design employed pressure sensors designed for detection of an explosion anywhere in the space. An analysis of the initial tests (i.e., U8 to U12, and S1) indicated the need for a detector with a faster speed of response as discussed in Section 2.4. Consequently, the primary detection mode for this sytem was changed to ultraviolet (UV) sensing. When this change was made the location of the ignition source was known, so a single ultraviolet sensor was used realizing that multiple sensors giving complete surveillance of the hazard area could be easily added if needed. This point will be discussed in further detail in the section on guidelines for evaluating explosion suppression systems. UV detector B was used during these tests. Its characteristics are described in Table 5. It was located just inside and near the overhead of the starboard wing and aimed at the general area of ignition as shown in Figures 19 and 20.

Extinguishers - The high rate discharge extinguishers for the candidate suppression agents were located within the hazard area (see Figures 20 and 21). Both the dispersal patterns of the high-rate discharge extinguishers and the concentrations required in order to provide suppression and complete inerting of the pump room were considered when placing the extinguishers. The extinguishers are spherical with a flanged opening at the bottom. A rupture disc is used to seal this opening and an explosive initiator (0.40 gms PETN) is placed just inside this disc as shown in Figure 22. An elbow is attached to the flange to redirect the flow of the agent and a spreader is secured on the end of the elbow. The extinguishers were then charged approximately 2/3 full with the candidate agent and pressurized to 325 ± 5 psig (22.8 ± 0.35 Kg/cm^2) with compressed dry nitrogen. A signal from the control unit (initiated by the detection system) would fire the initiator which would rupture the disc and permit the rapid expulsion of the agent under the 325 psig driving force. Motion pictures of these extinguishers being discharged in the open show the distribution pattern to be about a 160 degree cone. The average velocity of the agent over the first 100 milliseconds is typically 100 ft/sec (30.5 m/sec) as shown in

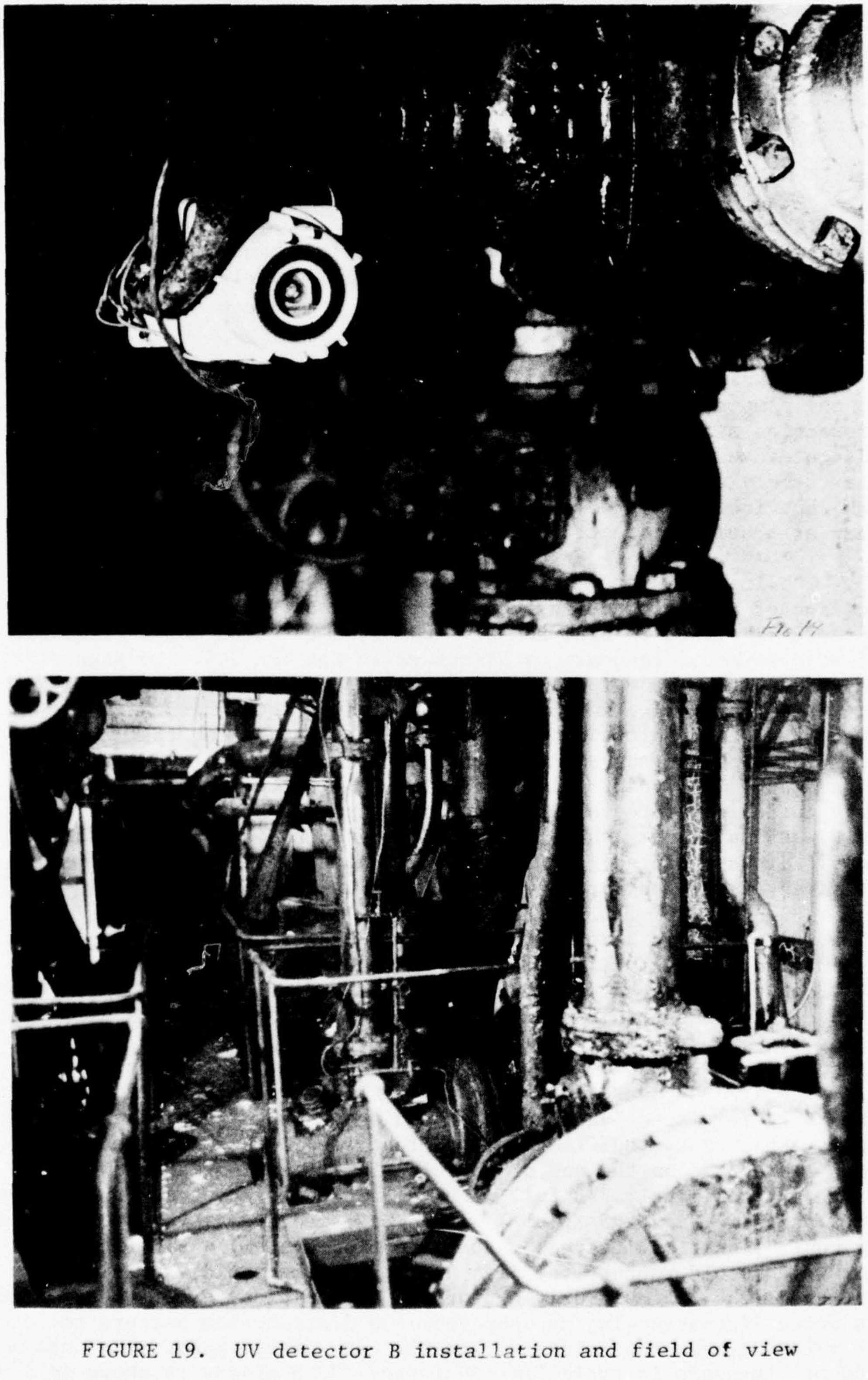
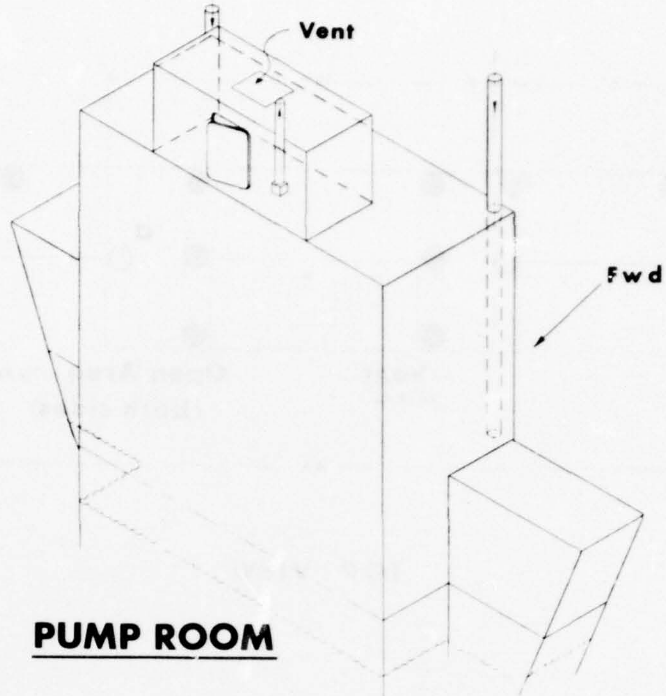


FIGURE 19. UV detector B installation and field of view



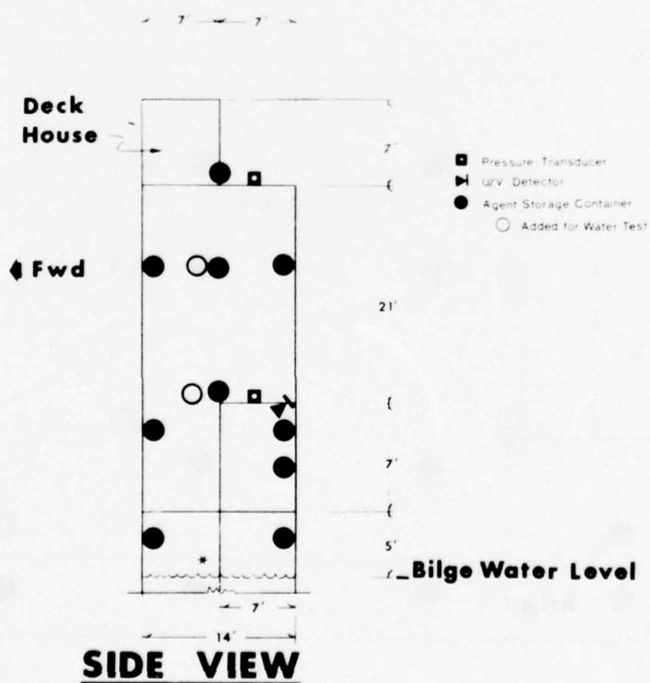
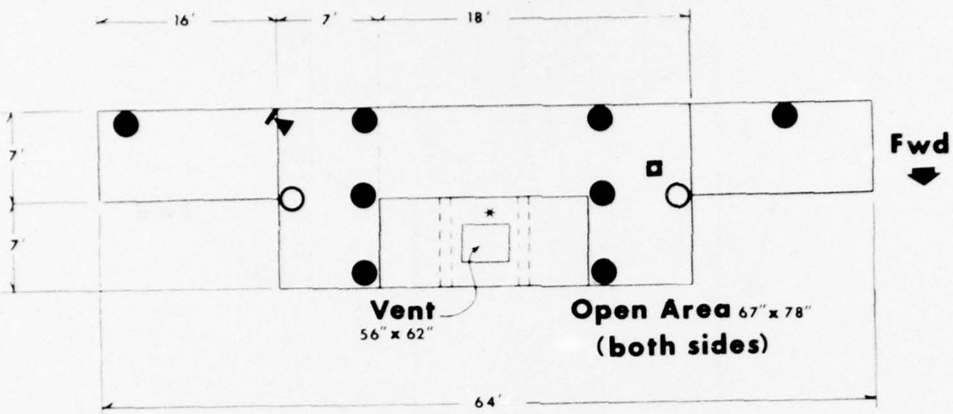
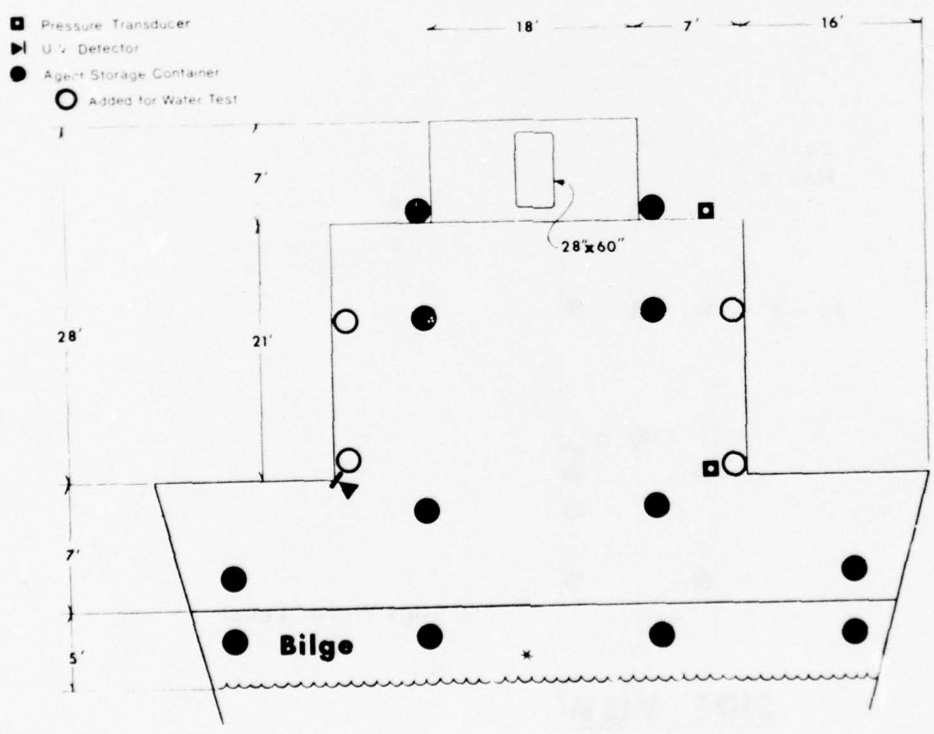


FIGURE 20. Arrangement of explosion suppression system A in pump room (2 pages)



TOP VIEW



FRONT VIEW

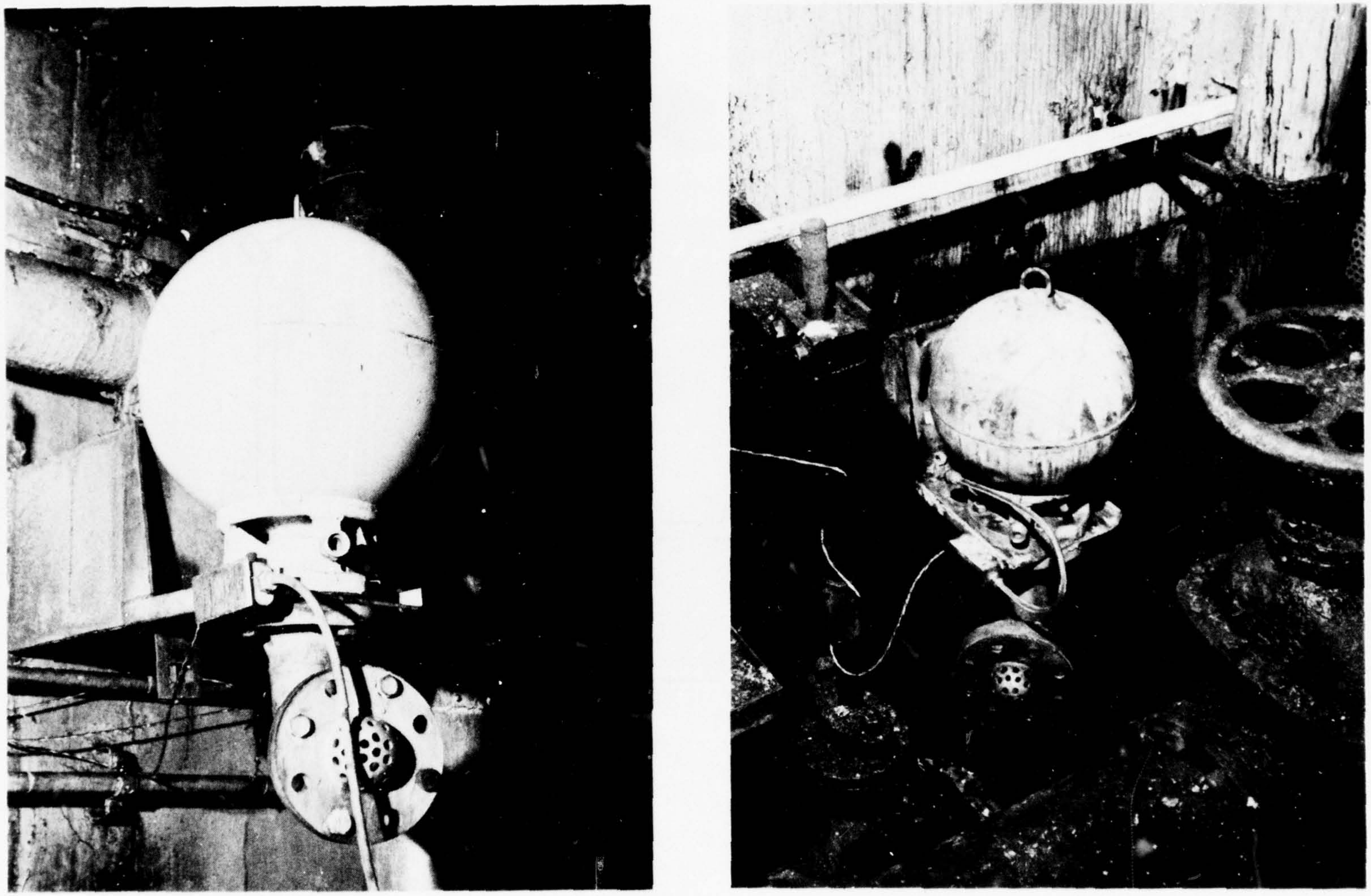


FIGURE 21. Typical high rate discharge installations

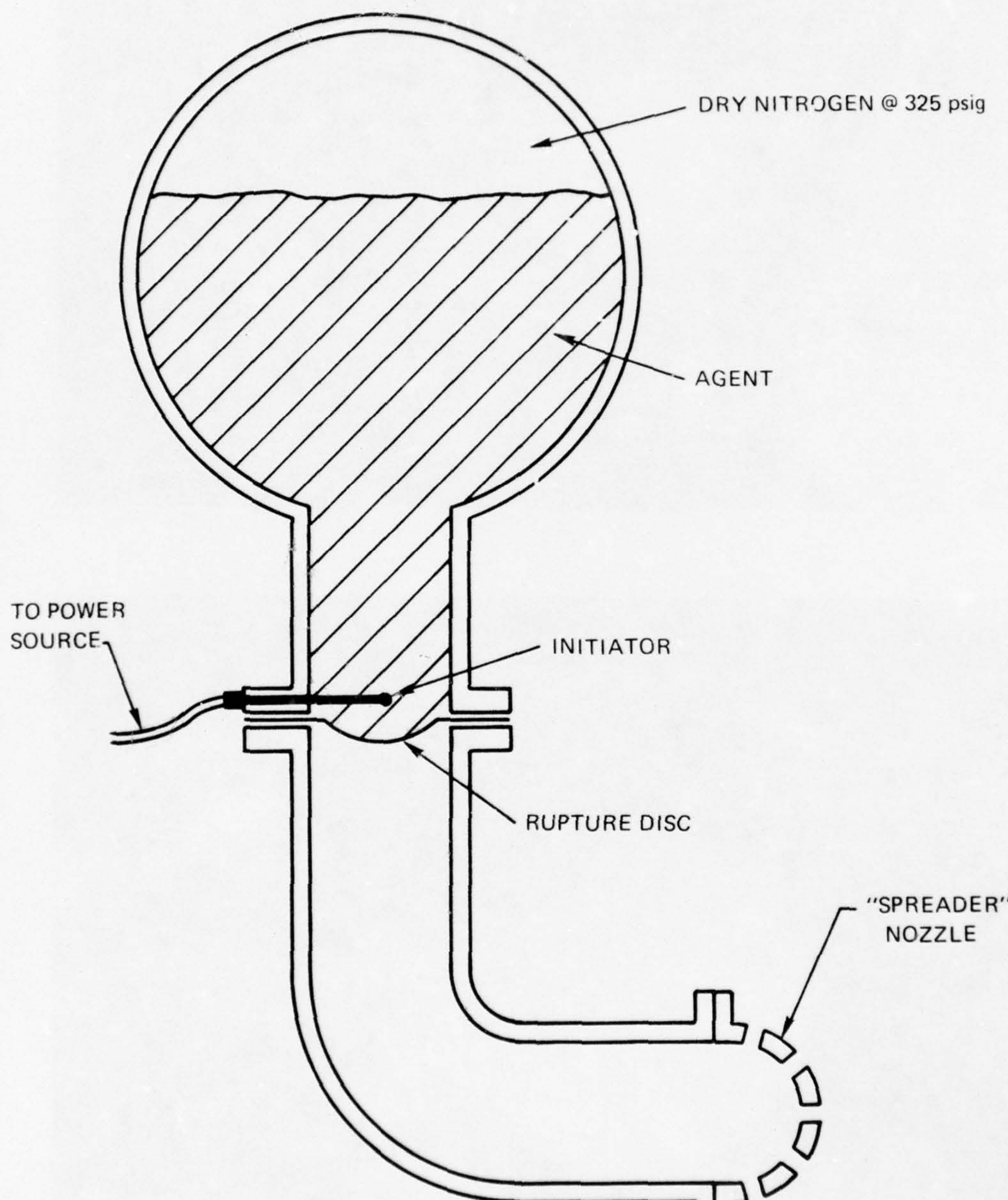


FIGURE 22. Cutaway drawing of high rate discharge extinguisher used in system A

Figure 23. The velocity increases slightly with decreasing agent density. The agents which vaporize rapidly such as Halon 1301 tend to slow more quickly than Halon 2402. The maximum effective range taken as the range at 100 milliseconds is approximately 11 feet (3.4m) for Halon 2402.

Control Unit - A standard "off-the-shelf" control and power unit was used to complete the system. This control unit provides all necessary functions, such as the firing signal to the electrically operated initiators, complete supervision of all external wiring to the detectors and suppression devices, a ground detection circuit, automatically switched standby power, and system test capability. A schematic of the circuitry used is presented in Figure 24. Note that the initiators for the high rate discharge extinguishers are wired in series. A more complete discussion of each of the system components will be provided in the section guidelines for evaluating explosion suppression systems.

3.2 Test Program and Results

Explosion suppression system A was employed for evaluating water, Halon 2402, Halon 1211, and Halon 1301 as suppressing agents for n-Hexane and propane explosions. The characteristics of these agents which are relevant to their dispersion and suppression capabilities are shown in Table 8. A summary tabulation of the principle features of each test conducted (i.e., S1 through S10) are shown in Table 9. The pressure time traces for these tests are shown in Figure 25. The starting point for each of these traces was taken at the instant the suppression system actuated. This was determined through electrical connection to the initiator circuit. Ten minutes after each test a 37,500 cfm blower was turned on to ventilate the pump room and remove all toxic gases.

It is apparent from the results that Test S1 which employed Halon 2402 in an attempted suppression of a Hexane explosion was not successful. The reason for its failure was that the pressure detection sub-system employed was not fast enough. It did trigger the high rate discharge extinguishers at the predetermined 1/2 psig point (equivalent to 0.06 seconds after time zero on the graph in Figure 25) but there were only 0.02 seconds from this point to the maximum pressure. Twenty milliseconds is not enough time for the agent to blanket the space and thus the explosion was not totally suppressed. A comparison of this pressure-time trace and the one for Test U28 indicated that a very minor amount of suppression (i.e., approximately 2.7 psig (0.19 Kgm/cm^2) reduction in pressure) may have occurred but this is not significant.

Suppression Tests S2 through S10 were considered successful. The primary differences between these tests and Test S1 were that propane was the fuel instead of n-Hexane and a UV detector was used instead of pressure detectors. The UV detectors are believed to be the reason for success since the unsuppressed n-Hexane and propane pressure time traces are very similar.

All indications show that the propane explosions developing during these suppressed tests were the same as those previously characterized (i.e., U25 and U31). The conditions outlined in Table 7 were held as constant as possible. The flame colors and fireball growth were similar during the initial stages. The average time from ignition (i.e., actuation of

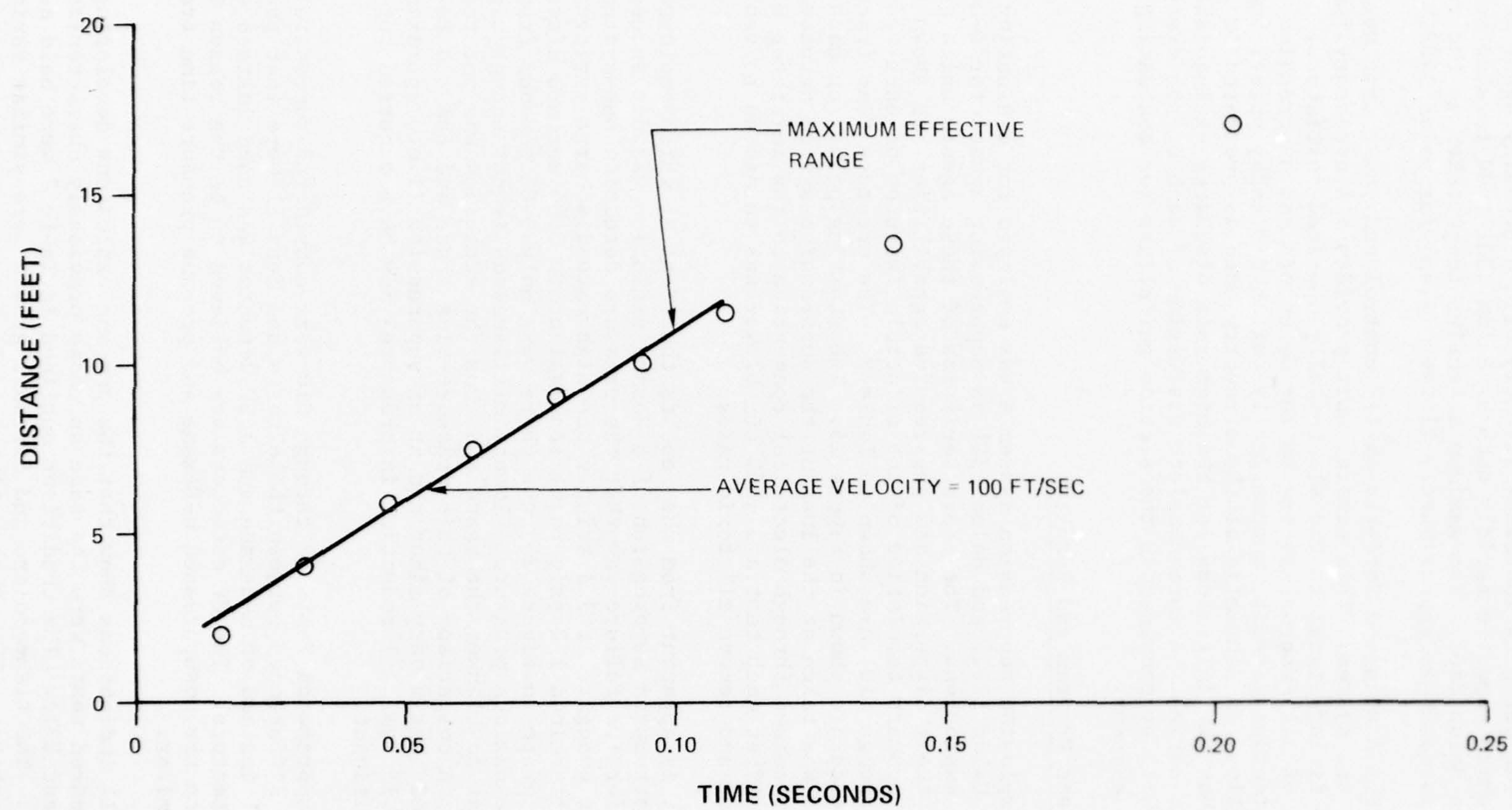


FIGURE 23. Typical curve for a Halon discharged from a high rate discharge extinguisher

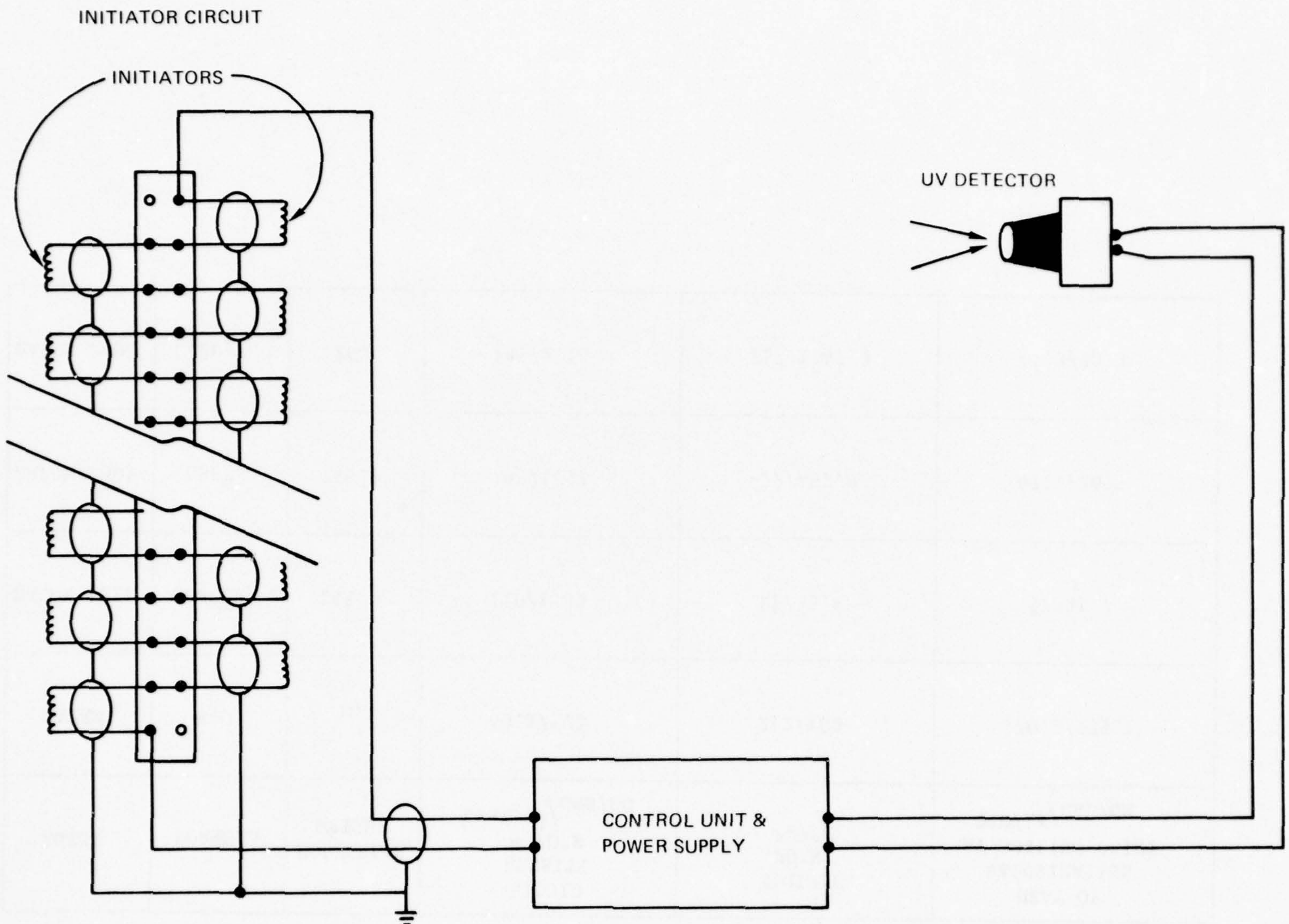


FIGURE 24. Schematic of detector and initiator circuitry for System A

TABLE 8 - PHYSICAL PROPERTIES OF WATER, HALON 1211, 1301, AND 2402

AGENT	FORMULA	MOLECULAR WEIGHT	LIQUID DENSITY @ 70°F LBS/FT^3/GMS/CC	BOILING POINT °F/°C	HEAT OF VAPORIZATION AT BOILING POINT BTU/LB/CAL/GM
WATER	H_2O	18	60.1/1.0	212/100	970.3/539.1
HALON 1211	$CBrClF_2$	165.4	110/1.83	25/-3.9	57/31.7
HALON 1301	$CBrF_3$	148.9	98/1.57	-72/-57.8	47.7/26.5
HALON 2402	$C_2Br_2F_4$	260	135/2.16	117.1/47.3	45.3/25.3

TABLE 9 - PRINCIPAL CHARACTERISTICS OF PROPANE EXPLOSION SUPPRESSION TEST S1 THROUGH S10

TEST NO.	AGENT		NUMBER OF EXTINGUISHERS	MAXIMUM PRESSURE (PSIG)±0.2	TIME FROM IGNITION TO SYSTEM ACTUATION (SEC)±0.002	TIME FROM SYSTEM ACTUATION TO PMAX (SEC)	DATA FROM STBD/64 CAMERA				NOTES
							AGENT CONTACT WITH FIREBALL				
	TYPE	QTY (LBS)					AT TIME (SEC)±0.005	RADIUS OF FIREBALL (FT)±15%	TIME OF FLAME OBLITERATION (SEC)±0.005	AFTERBURN TIME (SEC)±0.01	
S1*	HALON 2402	2126	18	10.1	-	0.08± 0.005	-	-	-	-	*TEST FUEL WAS n-HEXANE DID NOT SUPPRESS
S2	HALON 2402	2126	18	0.5	0.760	0.39±0.02	0.12	3.3	0.72	0.72	
S3	HALON 1211	1632	18	0.8	1.065	0.33±0.02	0.31	6.3	0.89	NONE	
S4	HALON 1301	1400	18	0.8	0.695	0.28±0.01	STBD/64 CAMERA DID NOT OPERATE				ORANGE-YELLOW SMOKE EXPELLED FIRST SMOKE (NO BLOWERS ON)
S5	WATER	1190	20	5.1	0.890	0.275± 0.005	0.12	4.2	0.58	NONE	
S6	HALON 2402	1285	18	0.5	1.060	0.35±0.02	0.09	1.7	1.12	1.10	ORANGE-YELLOW SMOKE 1.2 SEC AFTER FIRST SMOKE (NO BLOWERS ON)
S7	HALON 1211	1088	18	0.7	0.745	0.33±0.02	0.14	4.9	0.84	NONE	
S8	HALON 1301	934	18	0.3	0.980	0.36±0.01	STBD/64 CAMERA DID NOT OPERATE				
S9	WATER	1364	20	5.0	0.775	0.265± 0.005	STBD/64 CAMERA DID NOT OPERATE				
S10	HALON 1301	618	18	0.6	0.810	0.34±0.02	0.09	1.6	0.67	8.54	AFTER BURN INCLUDED TWO SEPARATE PHASES

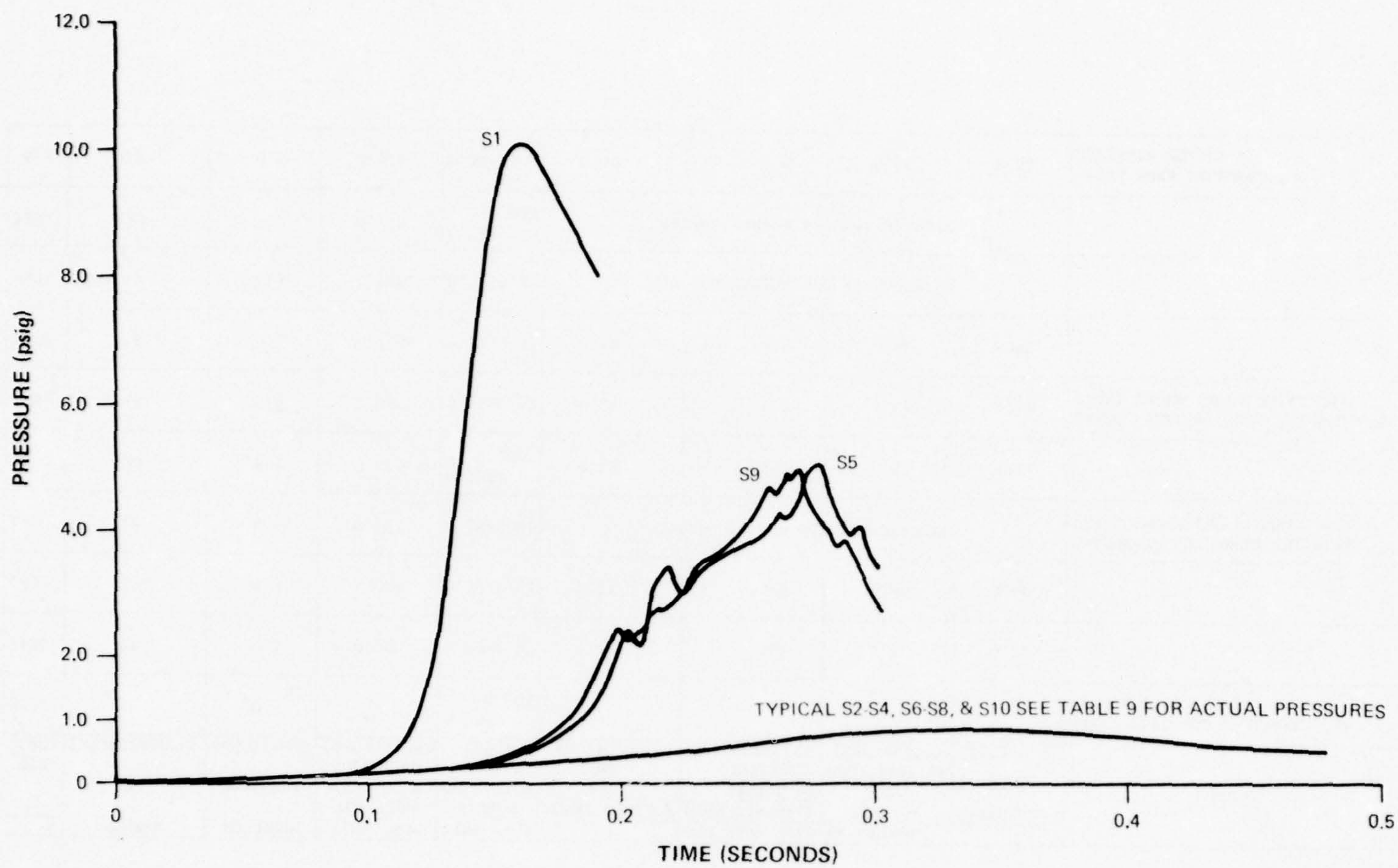


FIGURE 25. Pressure-time traces for Tests S1 through S10

the spark igniter) to system actuation were system actuation is less than 10 milliseconds after UV detection was slightly longer than the average time from ignition to UV detection in tests U15 to U27 (i.e., 0.86 vs. 0.69 seconds). However, the range of these times (0.70 to 1.07 seconds) falls wholly within the range for tests U15 to U27 (see Table 6).

Fireball Size - One difficulty in analyzing the data to determine the effectiveness of each agent is that the agent did not contact the same size fireball in each test. Slight variations in detection timing and fireball velocity cause variations in the size of the fireball at the moment of agent contact. For Tests S2 through S10, the time of contact ranged from 0.09 to 0.31 seconds while the radius of the fireball ranged from 1.6 to 6.3 feet (0.49 to 1.92m) as shown in Table 9. This data was taken from movie footage obtained with the starboard/64 camera. The area of flame front varied from 32.2 to 498.8 square feet (2.99 to 46.3m^2). Since extinguishment occurs in the area of surface flaming it is apparent that Test S3 presented a difficult suppression problem and Tests S6 and S10 presented easy fireballs to suppress.

Toxic Gas Byproducts - In at least two cases, Tests S4 and S6, orange/yellow smoke was expelled from the hatch on top of the pump room deck house (see comments in Table 9). In test S4 this smoke was not expelled until after the ventilation blower (37,000 cfm) was activated. In test S6, however, the orange/yellow smoke was expelled approximately 1.2 seconds after the first visible smoke and prior to blower activation. This smoke was particularly dense. While no chemical analysis of the smoke was conducted it is believed to include bromine gas because of its color and the choking reaction experienced by observers.

Afterburning - From the unsuppressed tests it was determined that 12 pounds (5.44 Kg) of propane burns itself out in approximately 2.5 seconds. During several of the suppression tests considerable afterburning was observed from the internal motion pictures. The starboard/64 camera gave the best record of this afterburning since it was the closest to the fire and thus had less agent and smoke to obscure its view. Unfortunately, this camera did not operate properly for tests S4, S8 and S9 and so the data is not complete. In both tests using Halon 2402 as the agent (i.e., S2 and S6) considerable after burning occurred (see Table 9). After burning was not observed in either test which employed Halon 1211 as agent (i.e., S3 and S7). Three tests were conducted with Halon 1301. Afterburning was not observed for Tests S4 and S8, however this is not conclusive evidence since there were no internal cameras functioning in Test S4 and only the top/64 camera functioned in Test S8. Test S10 showed considerable afterburning. In fact, there were two afterburn periods which were totaled to produce the figure recorded in Table 9. The first of these started 0.98 seconds after the first visible flame and lasted until 1.73 seconds. The afterburning reappeared at 2.62 seconds and finally subsided at 9.52 seconds. No afterburning was observed for the water suppression attempts (Tests S5 and S9). This observation could be faulty for Test S9 because the top/488 camera was the only one which functioned.

An attempt to develop agent concentration versus maximum pressure requirements would be futile with the limited number of data points for each agent. A brief discussion of the observations for each agent tested should provide a qualitative "feel" for the minimum amount of agent required for successful suppression.

Halon 2402: This agent successfully suppressed explosions at application densities of 0.116 and 0.071 pounds/cubic foot (1.86 and 1.14 Kg/m^3). There are two factors which indicate that this lower density was approaching the threshold level for suppression. First, the agent was broken down to a very significant degree as evidenced by the orange/yellow smoke observed. Second, the agent reached the fireball more quickly (0.09 seconds) than in any other test except test S10. Thus the area of flame was smaller (36.3 sq. ft/3.37m^2) and extinguishment should have been easier. However, it took 1.03 seconds to totally obliterate the flame and severe afterburning occurred. One must assume that 0.071 pounds/cubic foot (1.14 Kg/m^3) of Halon 2402 was barely sufficient to extinguish the fireball and if the fireball had been any larger at agent contact the explosion would not have been suppressed.

Halon 1211: This agent was successful at application densities of 0.089 and 0.059 pounds/cubic foot (1.43 and 0.95 Kg/m^3). While the maximum pressures developed during these tests were slightly higher than in the Halon 2402 tests it is not significant since they were still less than 1.0 psig (0.07 Kg/cm^2). There is no indication from the data that the threshold application density has been approached.

Halon 1301: This agent was successful at application densities of 0.077, 0.051, and 0.034 pounds/cubic feet (1.23, 0.82 and 0.54 Kg/m^3). The lowest application density appears to be approaching the threshold for suppression. The evidence is similar to that for Halon 2402. While the agent reached the fireball very rapidly (0.09 seconds) and therefore the area of flame was small (32.2 sq. ft/3.37m^2), extinguishment was difficult. It took 0.560 seconds to totally obliterate the fireball and there was severe afterburning as previously discussed.

Water: This agent was only partially successful at application densities of 0.075 and 0.071 pounds/cubic foot (1.20 and 1.14 Kg/m^3). While it did reduce the pressure from that expected for an unsuppressed explosion, it only reduced it to 5.0 ± 0.2 psig (0.35 ± 0.014 Kg/cm^2). Considerably higher application densities would be required to achieve suppressions comparable to those of the Halon agents.

4.0 EXPLOSION SUPPRESSION SYSTEM B

Explosion suppression system B was a conglomerate of components integrated into a total system. It consisted of "off-the-shelf" detectors, experimental extinguishers, and a control/power circuit designed for the tests. It was designed to protect the entire volume including the wings with total detection and extinguishing coverage. The author placed the hot wire igniter in a location he considered realistic (i.e., low in the space) and difficult to detect after the entire system had been installed.

4.1 System Design

A suppression system developed for the U. S. Bureau of Mines[8] was used with ultraviolet detectors for instantaneous (<0.010 sec) response to the development of a fireball. It combined two design philosophies. From the suppression standpoint, the system was designed to deliver sufficient

dry chemical for suppression to every part of the pump room within 50 milliseconds from the moment of release. The detection system used to initiate the release of the suppressant consisted of ten ultraviolet detectors placed throughout the pump room so that an ignition occurring in any location in the pump room would be detected within 10 milliseconds after sighting the fireball. This combination of virtually instantaneous detection and rapid delivery of dry chemical suppressant was an extension of the approach developed and used successfully in the suppression of more than 250 ignitions generated in a methane/air/coal dust environment[8,11]. Despite the extensive test background, however, the system must be considered experimental since it has not as yet been applied on a commercial basis.

Extinguishers - The design concentration of dry chemical was 0.01 pounds per cubic foot (0.16 Kg/m^3). Eighteen "cannons" of the type illustrated in Figure 26 were distributed throughout the pump room as shown in Figures 27 and 28. The "cannons" consist of a high pressure cylinder pressurized to 600 psig (42.2 Kg/cm^2) using compressed dry nitrogen. The dip tube is open to the inside of the cylinder and filled with 10 pounds of dry chemical. It is provided with a closure member at the outlet of the cylinder in the form of a thin metal disc. Attached to the metal disc is an explosive charge (duPont "SSS" seismic electric blasting cap) capable of developing sufficient force to rupture the disc in less than one millisecond. It can be seen from the drawing that once the disc ruptures, the gas contained in the cylinder can escape only through the tube containing the chemical power, a fact which insures full discharge of the contents in the tube. Motion pictures of these extinguishers being fired in the open show the distribution pattern to be about a 30° cone for the first 6 to 8 feet. After this the powder mushrooms into an expanding cloud. The velocity of the dry chemical powder was 168^{+5}_{-30} feet per second ($51.2^{+1.5}_{-9.1}$m/sec) (see Figure 29) and it holds af effective pattern to approximately 50 feet (15m). The maximum effective range taken at 100 milliseconds is approximately 17 feet.

Dry Chemical Compaction - An important feature of this construction is that the chemical powder is stored in inert dry atmosphere and the powder grains are surrounded by molecules of gas at the evaluated pressure of the cylinder. When the pressurized cylinder is open and exposed to atmospheric pressure the gas molecules surrounding the chemical granules rapidly expand. The undesirable effects of packing or caking of the dry chemical is thus overcome. The extinguishing powders stored in this manner for periods in excess of a year have been found to be completely fluid and free of packing when removed for examination[8].

Detection - Ten supervisory detectors were used to provide response to the development of a propane/air fireball in the pump room. A typical installation can be seen in the pictures of Figure 26. They were all Type C UV detectors whose characteristics are listed in Table 5. They were connected so that a response of any one detector would activate the suppression system. Another detector of Type B in Table 5 was used exclusively to determine the exact time of ignition. This was accomplished by placing the UV detector approximately 3 inches (7.6 cm) from the hot wire ignition source as shown in Figure 14. The detector is blind to the radiation produced by the glowing nicrome wires, but as soon as the propane flame develops it

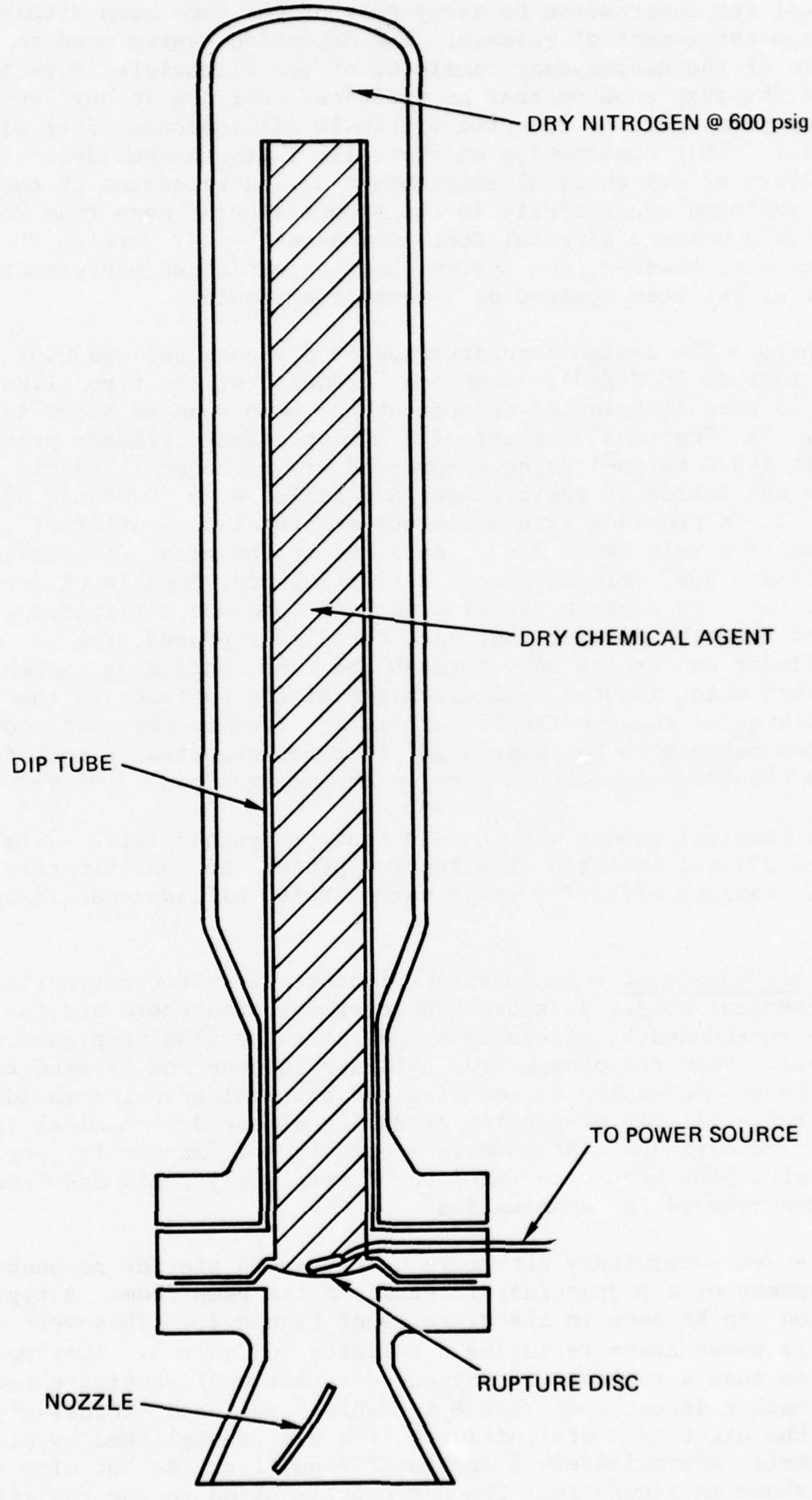


FIGURE 26. Cutaway drawing of extinguisher cannon

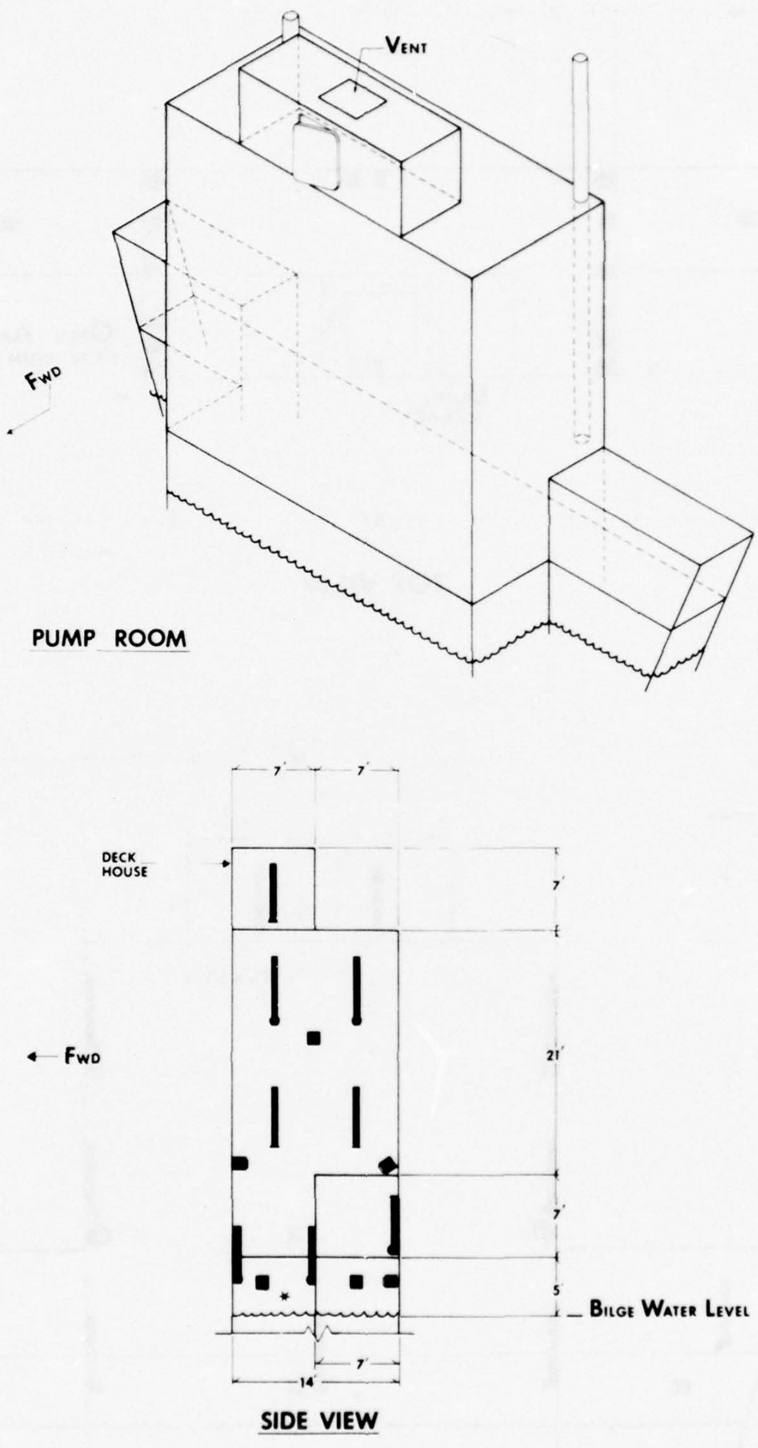
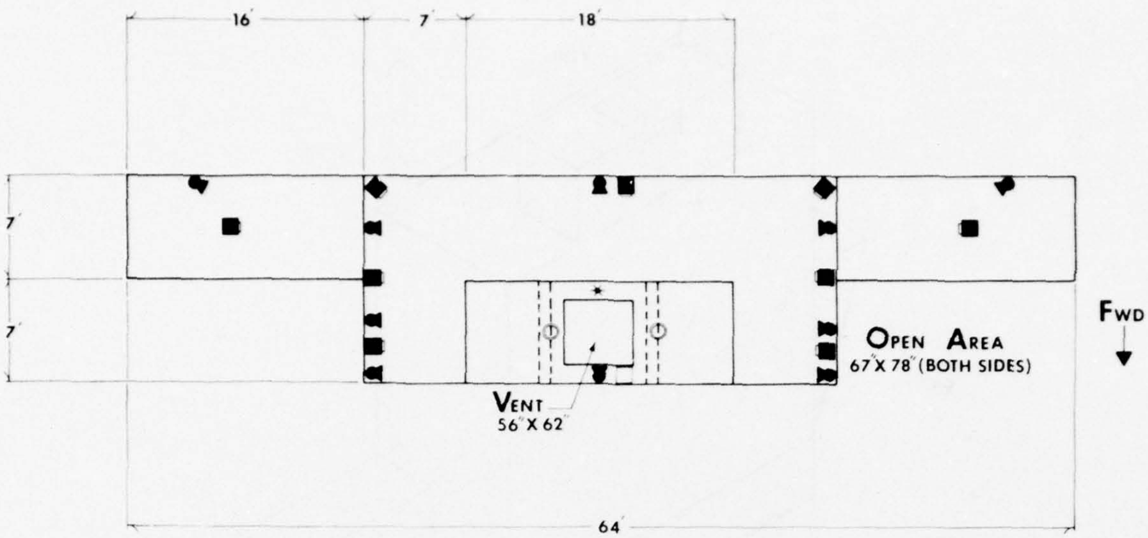
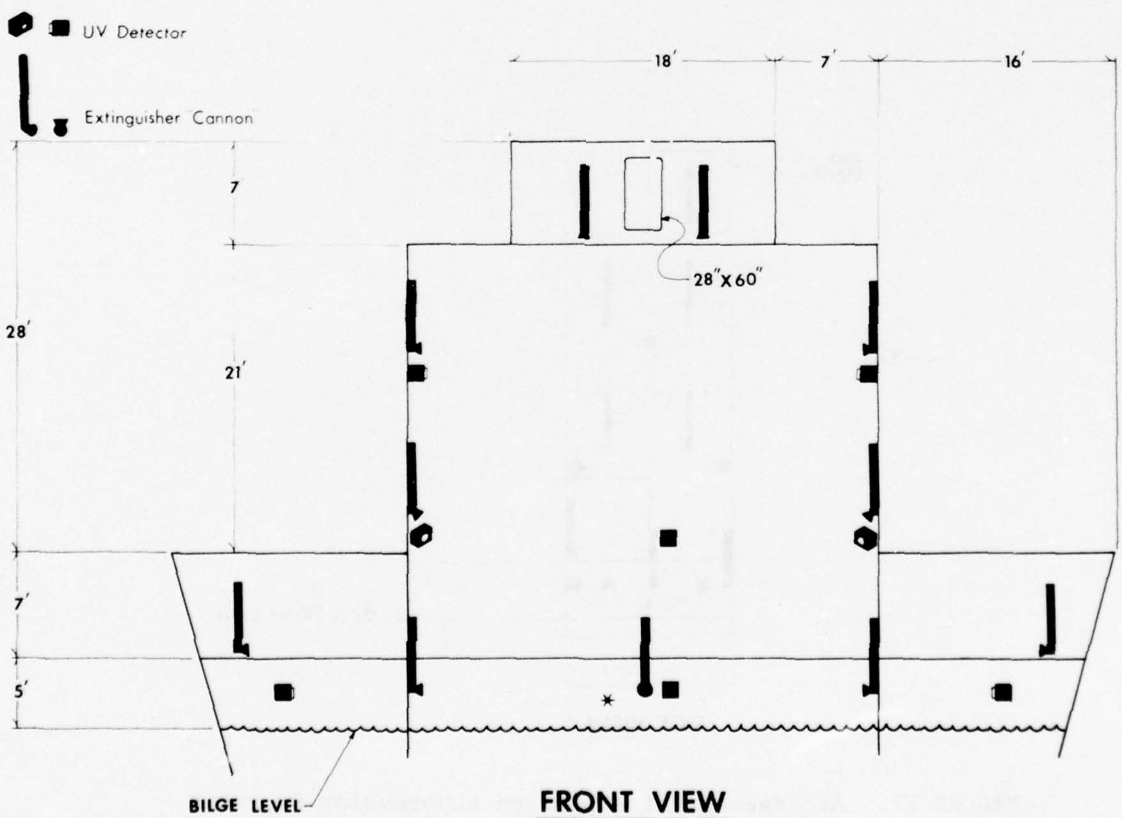


FIGURE 27. Arrangement of explosion suppression System B in pump room (2 pages)



TOP VIEW



FRONT VIEW

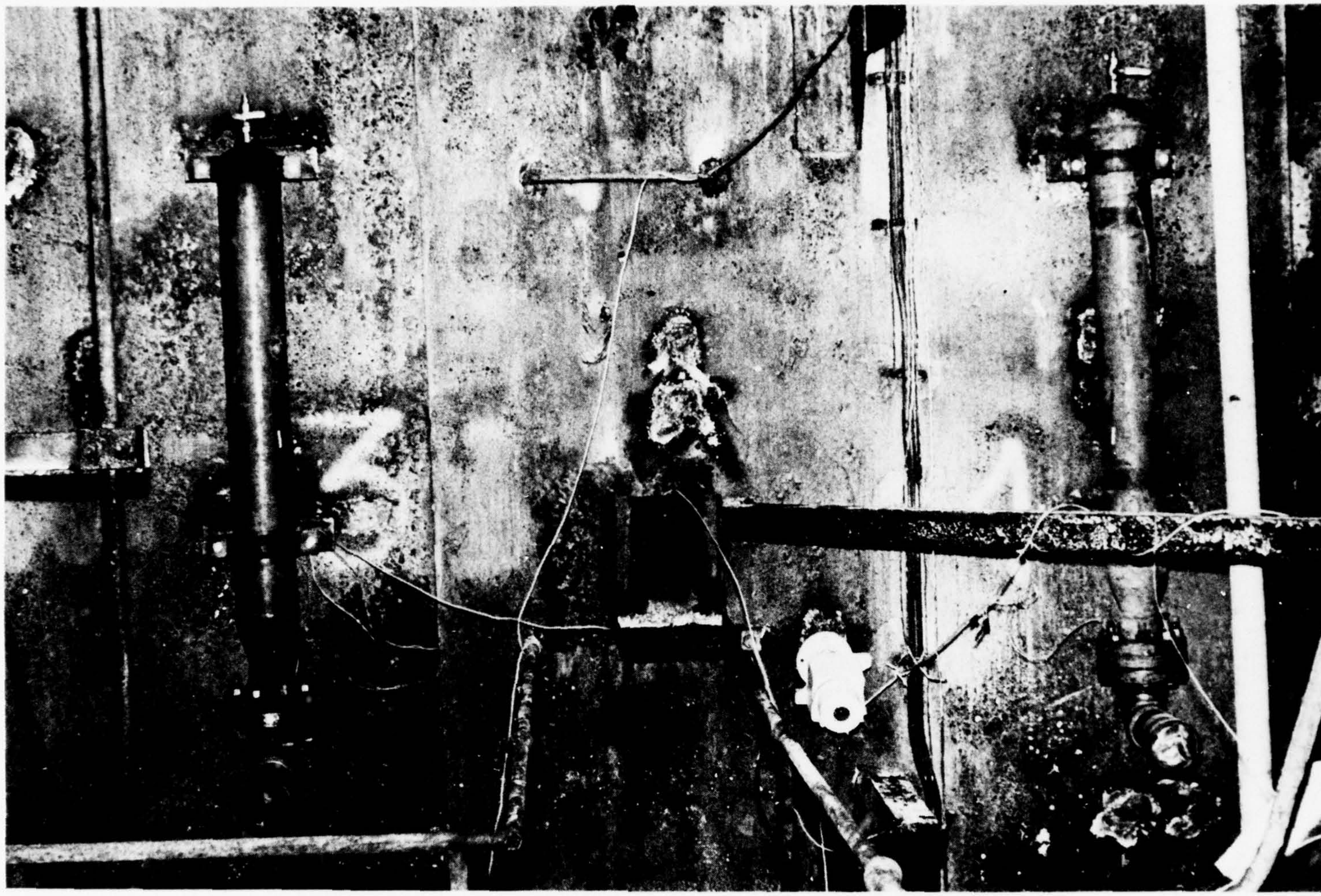


FIGURE 28. Typical extinguisher "cannon" installations

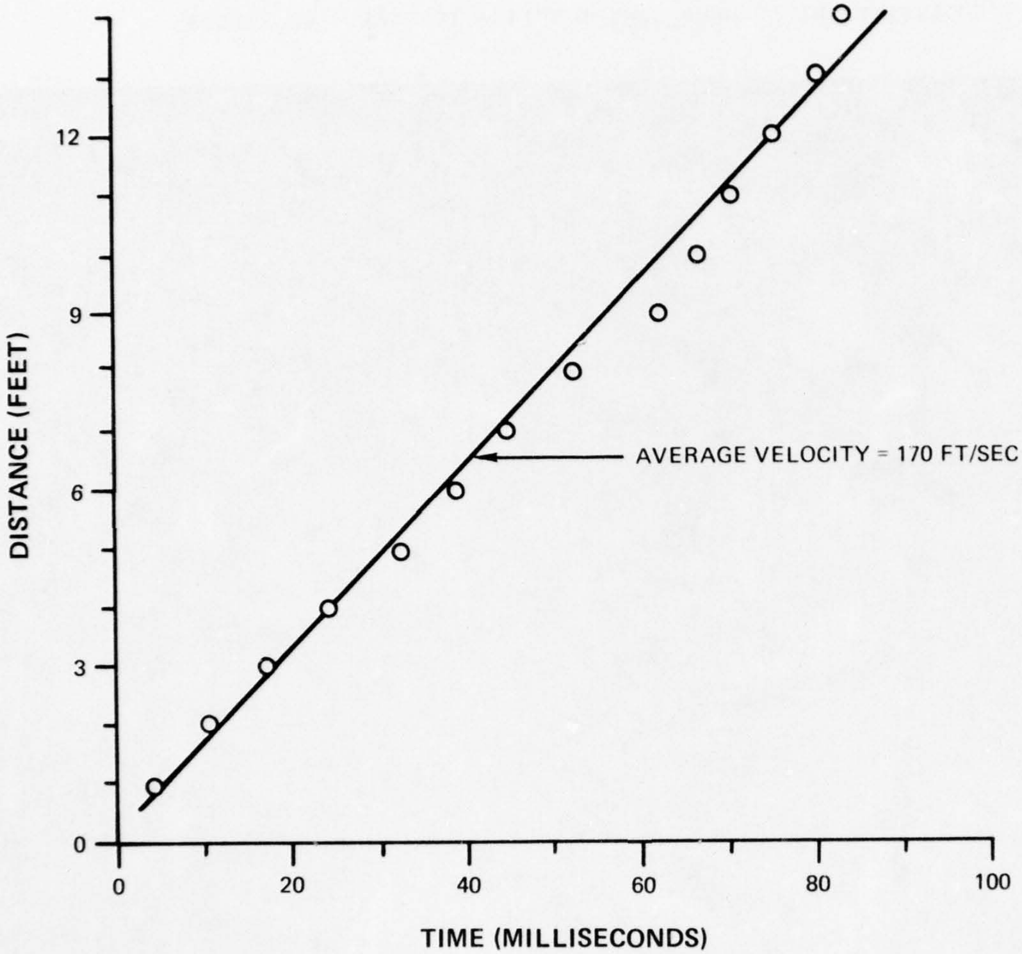


FIGURE 29. Typical curve for dry chemical discharged from an extinguisher cannon

detects it and thus the ignition time is established. This detector was adjusted to respond to a saturating signal within 4 milliseconds which means that time 0 obtained in this manner actually was time 0 plus 4 or 5 milliseconds.

Control Unit - The detection/control/power circuitry is illustrated in Figure 30. It provided the capability of identifying which UV detector triggered the system, continuously checking the igniter circuits for open circuit conditions and signals to the recording instrumentation for ignition detection, supervisory UV detection and suppression system actuation (i.e., igniters fired). The igniters were grouped in four parallel banks of igniters arranged in series.

4.2 Test Program and Results

This explosion suppression system was used to evaluate the effectiveness of Purple K (potassium bicarbonate) dry chemical agent and a fluorinated liquid agent designated FC-77 on the propane explosions previously described. Primary characteristics which effect the explosion suppression capabilities of these agents are listed in Table 10. The principle results of the testing are summarized in Table 11 and Figure 31. Subsequent to each dry chemical test the pump room was given a complete water washdown and ventilated with a 37,500 cfm fan to remove all powder clinging to surfaces.

FC-77 - The suppression attempt with FC-77 (Test S14) was unsuccessful. In fact, pressure obtained in the space was higher (1.5 ± 0.2 psig) than any of the pressures developed during the unsuppressed testing. The failure was caused by one bank of initiators which did not fire and thus the four cannons immediately above the bilge areas were not activated. It is interesting to note that the quantity of agent which resulted (163.2 lbs) actually enhanced the burning rate and thus the maximum pressure. This same phenomenon is possible with the Halon extinguishing agents when their concentrations are sufficiently low to put them into a flammable range and the pressure is increased during constant volume combustion.

Purple K - The dry chemical extinguishing agent successfully suppressed the propane explosion at an application density of 0.009 pounds/cubic foot (0.14 Kg/m^3). The suppression was marginal for application density of 0.006 pounds cubic foot (0.09 Kg/m^3) (Test S13) and was unsuccessful at the application density of 0.003 pounds cubic foot (Test(0.05 Kg/m^3) (Test S12). All indications were that the explosion developing was similar to those of Tests U25 through U27 and U31. The early flame speeds and flame colors were similar. In all tests the response time of the first supervisory detector to the presence of the fireball was between 18 and 25 milliseconds. In each case it was supervisory detector number 4 located in the aft corner of the pump room (162 inches (4.11m)) above the bilge water level, 10 inches (0.25m) off the port bulkhead and 16 inches (0.41m) forward of the after bulkhead) with the center line of its view aimed down 45° and forward to the center 45°. In each test all supervisory detectors responded to the presence of the fireball. Thus the response time of the detection system was very rapid and permitted actuation of the suppression system in time for the agent to reach the fireball before it had grown to 3.2 feet (0.97m) in diameter. There was no afterburning observed during these three suppression tests. A more detailed description of each of these tests follows.

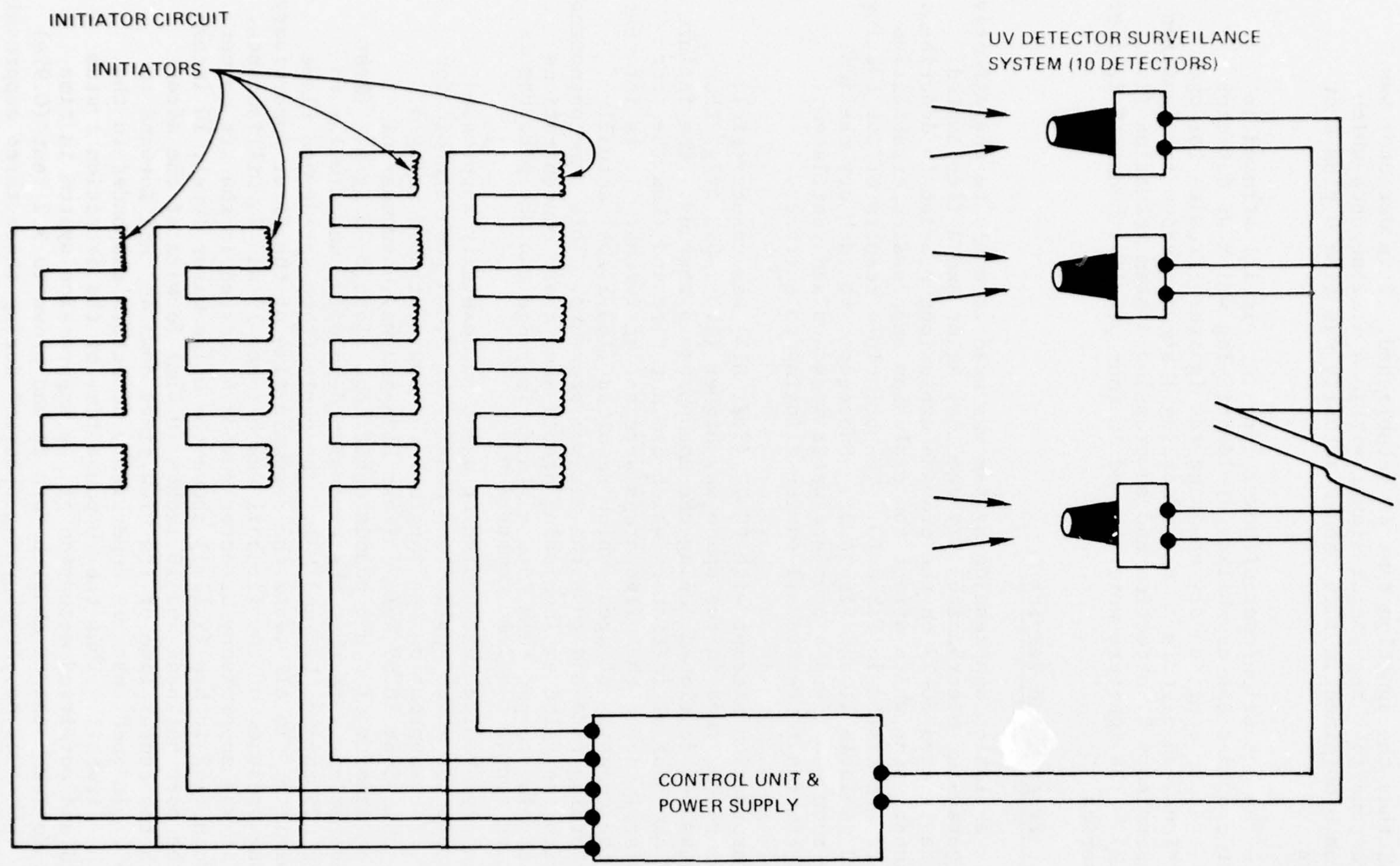


FIGURE 30. Schematic of detector and initiator circuitry for System B

TABLE 10 - PHYSICAL PROPERTIES OF PURPLE K AND FC-77

PURPLE K - DRY CHEMICAL		FC-77	
COMPOSITION:	$KHCO_3$ 93%	TYPE:	Mixture of fluorinated organic compounds
MOLECULAR WEIGHT:	100	AVERAGE MOLECULAR WEIGHT:	400
DENSITY:		LIQUID DENSITY AT 24°C:	1.78 gms/cm^3
Specific Minum	- 0.88 gms/cc	BOILING POINT:	97°C
Bulk	- 0.98-1.0 gms/cc	HEAT OF VAPORIZATION: AT BOILING POINT	20 cal/gm
Packed	- 1.35 gms/cc		
MOISTURE:	0.052%		
HYDROSCOPICITY:	1.63%		
MEDIAN PARTICLE SIZE:	25 MICRON		
SURFACE AREA:	46,000±1000 cm^2/gm		

TABLE 11 - PRINCIPAL CHARACTERISTICS OF PROPANE EXPLOSION SUPPRESSION TESTS S11 THROUGH S14

TEST NO.	AGENT TYPE	AGENT QTY (LBS)	NUMBER OF EXTINGUISHERS	MAXIMUM PRESSURE (PSIG)±0.1	TIME FROM IGNITION TO SYSTEM ACTUATION (SEC)±0.002	TIME FROM DETECTION TO SYSTEM ACTUATION (SEC)	TIME FROM SYSTEM ACTUATION TO PMAX (SEC)	DATA FROM STBD/64 CAMERA: AGENT CONTACT WITH FIREBALL AT TIME (SEC)±0.005	DATA FROM STBD/64 CAMERA: AGENT CONTACT WITH FIREBALL RADIUS OF FIREBALL (FT)±15%	DATA FROM STBD/64 CAMERA: TIME OF FLAME OBLITERATION (SEC)±0.005
S11	PURPLE K	170	17	0.2	0.026	0.002 ±0.0005	0.154 ±0.005	<0.09	<1.6	0.41
S12	PURPLE K	60	6	6.8/6.8	BEGINNING OF P/t TRACE NOT RECORDED- PEAKS SEPARATED BY 0.04 SEC.			STBD/64 CAMERA DID NOT OPERATE		
S13	PURPLE K	110	11	1.25	0.018	0.002 ±0.0005	0.655 ±0.005	<0.09	<1.6	1.25
S14	FC-77	EXTINGUISHERS DID NOT ACTUATE DUE TO A SHORT TO GROUND IN THE INITITION CIRCUIT.								

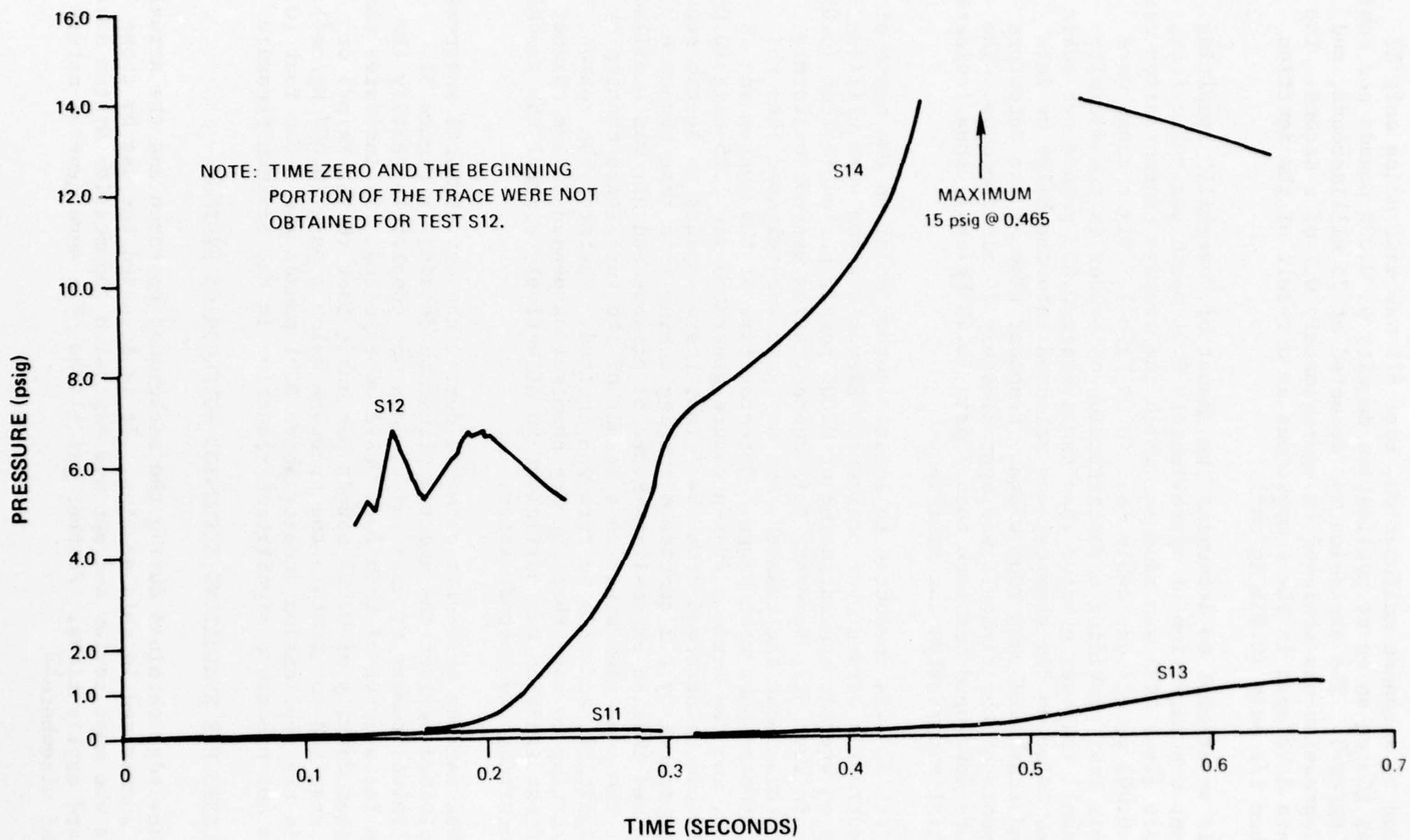


FIGURE 31. Pressure-time traces for Tests S11 through S14

Due to a cannon malfunction, test S11 was made using only 17 cannons thus giving an agent application density of 0.009 pounds per cubic foot.(0.14 Kg/cm^3). The explosion was detected at 25 milliseconds, and complete suppression was achieved in approximately 0.7 of a second. The over-pressure developed in the compartment as a result of the ignition was less than 1/2 psig (0.035 Kg/cm^2).

In an attempt to determine the amount of "overkill" resulting from an agent concentration of approximately 0.01 pound per cubic foot, a second test (Test S12) was made for which the average concentration was reduced to 0.003 pounds per cubic foot (0.05 Kg/m^3). Six cannons were used for this test providing a concentration of powder in the vicinity of the fireball that was greater than the average 0.003 pounds per cubic foot figure. Also no dry chemical was released into the bilge or into the port and starboard pump room wings. Response time of the detectors to the presence of the fireball was approximately 25 milliseconds. The over-pressure developed was less than 7 psig (0.49 Kg/cm^2), thus indicating that a partial suppression was achieved.

Test S13 was conducted to locate another point on the curve of agent concentration versus over-pressure. Eleven cannons were utilized, thus giving an average concentration of 0.006 pounds per cubic foot (0.09 Kg/m^3). As in Test S12, however, this concentration was not uniformly distributed throughout the chamber, and no agent was released into the port and starboard pump room wings. Detector time of the system was 18 milliseconds, and the maximum over-pressure generated was 1.25 psig (0.088 Kg/cm^2). As can be observed from the films, there appears to be two separate ignitions separated by 2.2 seconds occurring during this test sequence. It is theorized that an explosive mixture of propane and air was expelled from one of the pump room wings as a result of the turbulence created by the first ignition, and this in turn was ignited. Whatever the reason, it is interesting to note that the dry chemical suspended in the chamber after the first ignition was sufficient to effectively control the second ignition occurring two seconds later.

The maximum pressures obtained during the dry chemical suppression tests are plotted against the agent application density in Figure 32. While the limited number of data points does not completely justify the curve drawn in, a curve of this form would be expected. It indicates that an application density of 0.007 pounds per cubic foot (0.112 Kg/m^3) or greater is required to maintain the pressure below 1 psig (0.007 Kg/cm^2). Increases in the application density above 0.01 pounds per cubic foot (0.16 Kg/m^3) does not produce a significant reduction in the maximum pressure.

5.0 GUIDELINES FOR EVALUATING EXPLOSION SUPPRESSION SYSTEMS

The knowledge obtained during the background research and the actual testing is summarized in this section. It is intended for use by those individuals who must review and approve explosion suppression system designs for shipboard applications. Further guidelines of a more general nature can be found elsewhere[12].

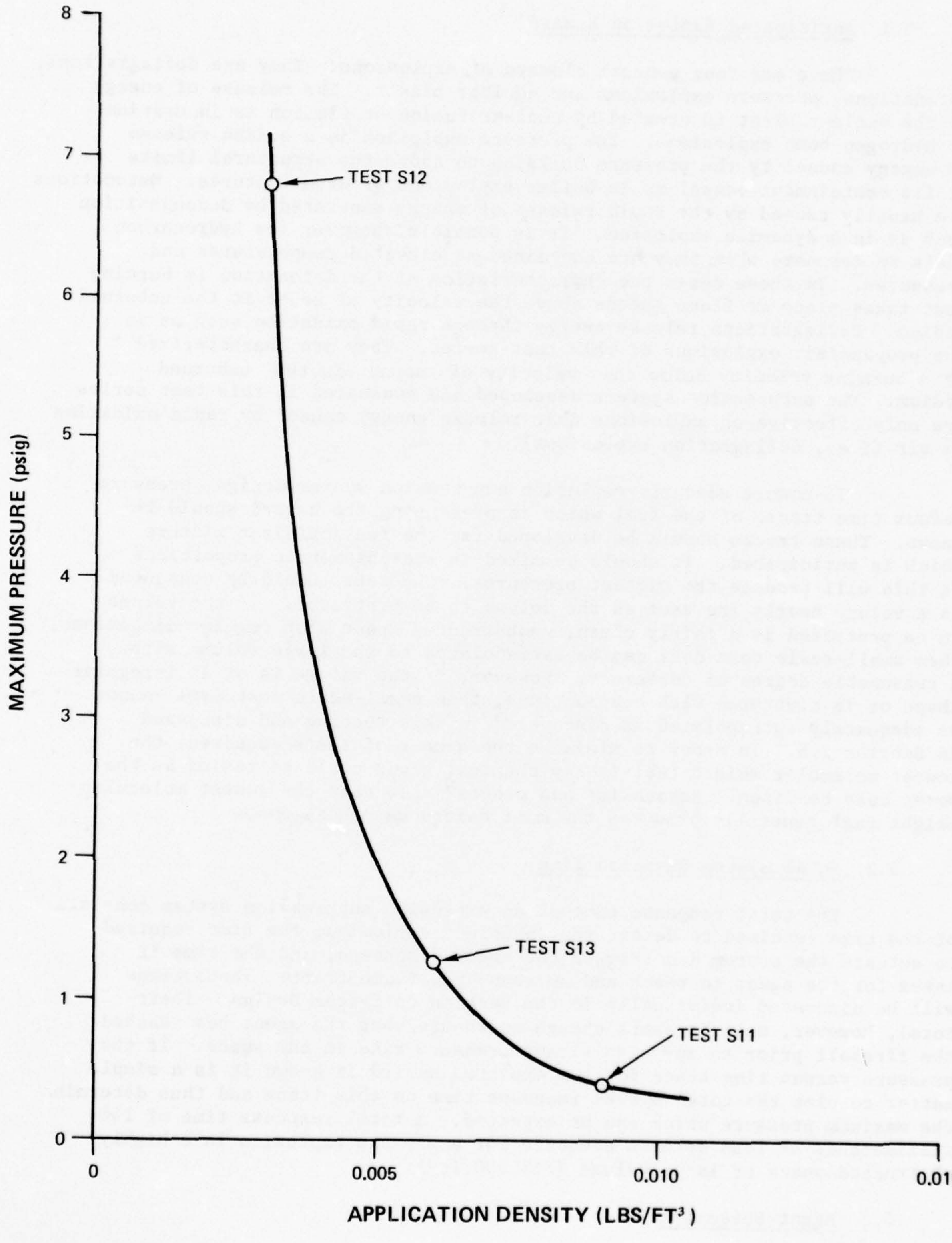


FIGURE 32. Maximum pressure as a function of application density of Purple K

5.1 Anticipated Explosion Hazard

There are four general classes of explosions. They are deflagrations, detonations, pressure explosions and nuclear blasts. The release of energy in the nuclear blast is created by nuclear fusion or fission as in uranium or hydrogen bomb explosions. The pressure explosion is a sudden release of energy caused by the pressure building to above the structural limits of its containment vessel as in boiler explosions or drum ruptures. Detonations are usually caused by the rapid release of energy generated by decomposition such as in a dynamite explosion. It is possible, however for hydrocarbon fuels to detonate when they are contained at elevated temperatures and pressures. In these cases the characteristics of the detonation is burning that takes place at flame speeds above the velocity of sound in the unburned medium. Deflagrations release energy through rapid oxidation such as in the propane/air explosions of this test series. They are characterized by a burning velocity below the velocity of sound in the unburned medium. The suppression systems developed and evaluated in this test series are only effective on explosions that release energy caused by rapid oxidation in air (i.e., deflagration explosions).

To ensure adequate explosion suppression system design, pressure versus time traces of the fuel which is presenting the hazard should be known. These traces should be developed for the fuel/oxidizer mixture which is anticipated. It should be mixed in stoichiometric proportions as this will produce the highest pressures. The test should be conducted in a volume nearly the same as the volume to be protected. If the volume to be protected is a fairly clean, unobstructed space with regular dimensions, then small-scale test data can be extrapolated to the large volume with a reasonable degree of certainty. However, if the volume is of an irregular shape or is cluttered with obstructions, then small-scale test data cannot be adequately extrapolated as discovered in this testing and discussed in Section 2.5. In order to minimize the number of tests required, the lowest molecular weight fuel in any chemical group could be tested as the worst case conditon. Zabatakis[7] and others[9] show that the lowest molecular weight fuel generally produces the most hazardous conditions.

5.2 Total System Response Time

The total response time of an explosion suppression system consists of the time required to detect the incipient explosion, the time required to actuate the system and trigger the agent discharge, and the time it takes for the agent to reach and surround the flame front. These times will be discussed individually in the section on System Design. Their total, however, must be short enough to ensure that the agent has reached the fireball prior to any significant pressure rise in the space. If the pressure versus time trace for the expected hazard is known it is a simple matter to plot the total system response time on this trace and thus determine the maximum pressure which can be expected. A total response time of 150 milliseconds or less appears adequate for a propane explosion in a highly obstructed space of large volume (>15,000 ft^3).

5.3 Agent Selection

Many factors must be considered in selecting the proper suppression agent for a given application. An evaluation of the following points will in most cases assist in the selection of the most effective agent.

a. The flammable characteristics of the combustible.

b. Suppression effectiveness.

c. Cleanup.

d. Cost.

e. Operating conditions.

f. Toxicity.

The major requirement of any suppressant is that it be contained in fluid form under pressures as high as 600 psig in order to provide sufficient propulsive force to carry the agent over the distance necessary to complete the required high speed suppressing action. While a hazard such as a pump room can be normally considered an unmanned area aboard a tanker there are certain conditions under which personnel might be in the area at the start of an explosion. Therefore, toxicity as well as agent concentration would be a significant factor if a Halon were to be selected as the suppressing agent. The agents considered in this particular test series were water, three halogenated hydrocarbons (Halon 1301, 1211, and 2402) and Purple K dry chemical. Considerations relative to their selection are discussed below.

5.3.1 <u>Water</u>

The mode of suppression action for water is purely physical depending principally on its high heat capacity and latent heat of vaporization to cool the reaction. There is some oxygen dilution achieved but this effect is secondary. Water has the advantage of being plentiful, inexpensive, completely safe to personnel, and very easy to recharge. It has been used successfully to suppress methane explosions in a simulated coal mine[13]. Its principal disadvantage is that it will not provide a continuing inert atmosphere following knockdown of an incipient explosion. When one considers the economics of the system, then water being far cheaper than any of the Halons becomes a suitable candidate. This cost saving is somewhat negated by the fact that at least twice as much water and therefore twice as many high rate discharge extinguishers are required for water as for any of the Halons.

5.3.2 <u>Halons</u>

Three of the five agents tested in this series are the so-called vaporizing type. They are halogenated hydrocarbons, and although their entry into the incipient flame zone does produce a cooling effect on the reaction, their principal mode of action is one of chemical inhibition[14]. Inasmuch as the combustion reaction is dependent upon the initiation and branching of the reaction chain within the flame zone, it can be suddenly arrested by forcing the termination of these chains. The hydroxyl (OH) free radical is constantly being regenerated and consumed during the combustion process. It is evidently essential to the branching of chains and thus to flame propagation. In the heat of the fire the halogenated hydrocarbons decompose with ease into free radicals of the particular Halon involved (i.e., F, Cl, Br, or I). These free radicals eliminate hydroxyl free radicals by causing them to combine. An example involving bromine follows:

$$CH_3Br + heat \rightarrow CH_3^* + Br^*$$

$$C_3H_8 + Br \rightarrow C_3H_7 + HBr$$

$$OH + HBr \rightarrow Br + H_2O$$

$$\text{Net } C_3H_8 + OH \rightarrow C_3H_7 + H_2O$$

The Halon first dehydrogenates propane (as an example) forming a free C_3H_7 radical (which will be further attacked by more bromine) and hydrobromic acid. The latter substance reacts with the hydroxyl free radical forming water and releasing bromine for further use in dehydrogenating C_3H_8, C_3H_7, and other CH groups. Thus a counter attack has been launched at the "heart" of the flame resulting in its rapid extinguishment. The effectiveness of the Halon compounds as chain breakers is in the order of I>Br>Cl>F.

Halon 2402 (dibromotetrafluoromethane) - The principal advantage of this agent over the others is its boiling point (118°F). In normal operating temperatures it will be discharged and distributed as a liquid. This means that volume coverage can be achieved extremely rapidly because the higher inertia of a liquid will penetrate the spaces faster than if the agent vaporizes somewhere between the nozzle and the flame front as would be the case with the agents having lower boiling points. The maximum effective range is approximately 11 feet (3.4m) at 100 milliseconds. Also because of its higher boiling point it can be recharged without the use of any special transfer equipment.

Halon 1211 (Bromochlorodifluormethane) - This agent boils at a somewhat lower temperature (26°F). It will still afford a reasonably rapid coverage and suppression within the protected volume. It has the principal advantage of being the least expensive of the halogenated agents discussed herein.

Halon 1301 (Bromotrifluromethane) - This agent boils at -72°F and would probably vaporize within 1 foot of the discharge nozzle following an actuation. Therefore, the space may not be penetrated as rapidly or effectively as with either of the two agents mentioned above. The maximum effective range is approximately 8 feet (2.4m) at 100 milliseconds. Halon 1301 is the least toxic and, therefore, the safest of the three agents tested. It is the only halogenated agent currently rated by NFPA[15] as suitable for use in occupied spaces. The concentrations required for suppression of explosions, however, are in the range where prolonged breathing should be avoided even with this agent.

5.3.3 Dry Chemicals

The dry chemical powder employed during the test series was a potassium bicarbonate known commercially as Purple K. During other test programs tests were conducted with sodium bicarbonate and other extinguishing powders including ABC, potassium chloride and potassium carbamate. Purple K was selected because of experience gained regarding compaction[8], and because of the fact that the Coast Guard is generally familiar with and used Purple K. However, the other testing mentioned indicates that, from the standpoint of suppression, all the powders with the exception of sodium bicarbonate are about equal.

Others[16,21] have demonstrated that the particle diameter of the dry chemical is critical to extinguishment. Thus, the dominant considerations in selecting a dry chemical agent are powder compaction, particle size and possible corrosion effects both on the cannon itself and on the environment into which the chemical is discharged. Purple K is free flowing and considered one of the least corrosive dry chemicals used for extinguishing.

The weight effectiveness of dry chemicals compares very favorably with the liquid or vaporizing agents. They can generally be considered non-toxic, and the agent cost is considerably cheaper than for the Halons. One major problem which has been encountered in portable extinguisher installations is the long-term compacting of the pressurized powder in the containment vessel, particularly where process equipment may be subjected to continuous vibration. A related problem involves the very special attention which must be paid to the discharge nozzles and intermediate piping to avoid plugging. This compaction problem is largely eliminated in a super pressurized high rate discharge extinguisher if the extinguisher is pressurized with dry nitrogen as discussed in Section 4.1.

Dry chemical also shares a common shortcoming with water. At normal temperatures, both of the agents will "fall out" (not remain in suspension) whereas the Halons by virtue of their vapor pressure will maintain an inert atmosphere in the protected volume. The testing did indicate that the dry chemical powder will remain in suspension for well over a minute, however, tests to determine the maximum suspension time were not conducted. This fallout problem can be resolved if the system design engineer knows in advance the nature of the ignition source; i.e., is it transient such as a single electrostatic discharge or is it persistent as would be the case of a smoldering material or an overheated bearing.

Dry chemical discharged from a pressurized cannon of the type described in Figure 24 is capable of being rapidly delivered in a predetermined pattern over considerable distances. This is primarily due to the fact that the inertia of a powder will be greater than that of liquid or vapor. Observations of dry chemical cannons fired in the open indicate a projection distance of approximately 50 feet (15m) and a maximum effective range of 17 feet (5.2m) at 100 milliseconds.

5.4 *System Design*

The primary subsystems for an explosion suppression system are extinguishers, detectors, and the control unit. Each of these should be designed for the hazard anticipated and then integrated into a total system. Consideration for the design of each of these subsystems follows.

5.4.1 Control Unit

An extremely high degree of reliability is necessary to assure a successful suppression of any explosion. Consequently, the control unit must be designed to provide many functions. It is usually located in a non-hazardous area. The unit should provide complete supervision of all external wiring to the detectors and initiators (located within the agent storage containers), power to actuate the extinguishers, ground detection capability, and system test.

Redundancy provides a high degree of system reliability; therefore, while control units would normally operate from the ship's power supply, they must have a capability for automatic switching to standby battery power in case of primary power failure. A high level of energy must be provided to the initiators to insure their proper function, therefore capacitor discharge is usually employed. Again, redundancy in the form of a second capacitor will increase system reliability. The unit should also provide for remote fire alarm indication and equipment shutdown, as well as audible and visual indication that the system has fired.

5.4.2 Detectors

Proper protection for a space requires continuous surveillance of all areas. Thus a detection system usually employs a series of detectors placed to survey the entire volume to be protected. A certain degree of redundancy in the coverage of these detectors provides for detection reliability. The size of the fireball at agent contact is a function of the detection time. More rapid detection will provide for easier extinguishment. Thus the fastest detection system consistent with system cost and complexity should be employed. Detection could be provided by any of the following devices.

a. Pressure sensors

b. Fast response thermocouples

c. IR radiation detectors

d. Photo conductive light sensor with suitable UV filter

e. UV radiation detectors

The merit of these devices were examined during these tests and by others[13,21], with the following conclusions:

Pressure Sensors - The use of pressure sensors to detect the explosions generated during this test series was not acceptable. This is because the fireball had to grow to an unacceptable size before a detectable pressure was developed. Thus by the time the pressure detector triggered system actuation the explosion was beyond control. If the explosion had developed as predicted, and this is still anticipated for large regular unobstructed volumes, then a pressure detector could be used. They have the advantage of being inexpensive and uncomplicated which makes them reliable.

Fast Response Thermocouples - This type of device was rejected because the flame actually has to reach the thermocouple before it can respond reliably. Thus for a large volume enclosure an extremely large number of thermocuples would have to be placed in order to detect the fireball in its infancy. Another deficiency of the fast response thermocouple for shipboard application is its fragile nature.

IR Radiation Detector - This form of detection was eliminated because of the high probability of many false responses caused by extraneous IR sources.

Photo Conductivity Sensors/UV Filter - The photo conductive light sensor with a filter capable of passing a narrow band width of ultraviolet light had promise. It was evidently eliminated because of its reported loss of sensitivity when kept in the dark and because its response was too slow.

Ultraviolet Detectors - This type of detector has provided the most reliable and rapid detection of an incipient explosion when used in a total surveillance system. In general the UV detector with the fastest total response time, the narrowest spectral response range and the largest cone of vision will provide the best detection. Since the detector must be located within the protected space, it should be of intrinsically safe electrical design. While it is the best choice for an explosion suppression system, it does have certain limitations which are discussed below.

Insensitivity - The most serious problems that can develop within a detection system are those which would render the detectors insensitive to the presence of a developing fire or explosion. Ultraviolet detectors are dependent upon the excitation of a sensor and the sensor in turn is dependent upon an optical system to transmit the ultraviolet radiation. Accumulation of petroleum products on the optical surfaces of UV detectors can render them completely incapable of transmitting ultraviolet radiation with the result that the detector becomes "blind." There are techniques for self-checking the sensor and electric circuitry of UV detectors from a remote control station. These techniques can be automated to provide an alarm if the detector is blinded. The use of these techniques are preferable to the manual checking and cleaning of detectors on a periodic basis.

Another problem that may be encountered in the application of UV detectors is the dense accumulation of smoke which will absorb or block the transmission of ultraviolet radiation from the fire to the detector and thus in effect render the detectors useless. Detectors are available which allow for the detection of such accumulations of smoke as well as the detection of a fireball. The smoke detection results in the entry of a signal in the control room. This signal could be used to directly actuate extinguishing equipment or to produce a noticeable alarm.

False Alarm - All references have been to a UV detection system and it must be noted that UV detectors will respond to any source of ultraviolet radiation that falls within its sensitivity range. Most UV detectors are designed to eliminate interference from the UV component of solar radiation impinging on the detector directly or through reflection, by designing their sensitivity range to be substantially below the wave length of the sun's radiation reaching the earth as shown in Figure 33. A remaining source of intense ultraviolet radiation which could affect the response of a UV detector is the spark from electric arc welding. Care must be taken to ensure that welding operations are not carried out in an area where either direct or reflected radiation could reach an active UV detection system. It should also be noted that x-rays and gamma radiation will cause a response of UV detectors of Geiger-Muller type as used in most commercially available UV systems. Thus proper warning should be posted outside of spaces protected by explosion suppression systems employing UV detection so that the systems are deactivated during maintenance which employ any of these forms of radiation. Normally the effected space will be gas freed once the system deactivated prior to any welding operations being undertaken.

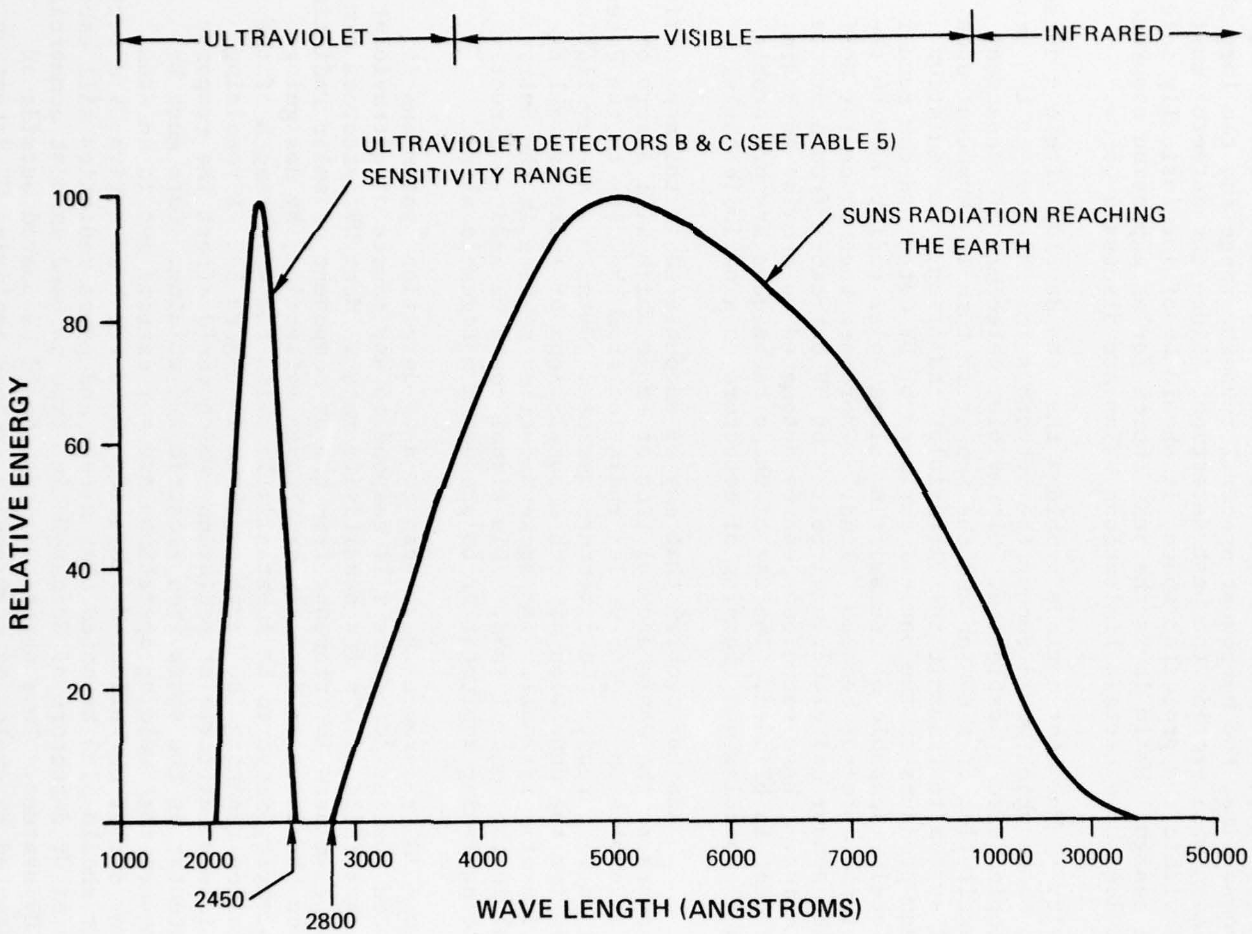


FIGURE 33. UV detector sensitivity in reference to other forms of radiation

Another inherent problem with Geiger-Muller tubes is that they have been known to produce significant false indications for reasons not immediately apparent. Research and testing into this question has identified cosmic radiation as one of the energy sources triggering false alarms. Recognizing this fact, UV detectors can be designed to require tube discharge rates of 10+ counts per second before detection is confirmed. Since cosmic radiation produces discharge rates significantly less than 10 it can be eliminated as a false alarm source.

The limitations discussed are not insurmountable but they do require careful design to minimize false alarms or no detection problems. In some cases it is recommended that the detection surveillance system be wired with pairs of UV detectors in series so that both must simultaneously sense the ultraviolet radiation before agent release. This provides a safeguard against agent release in the event that one detector false alarms. It also serves to desensitize the surveillance system and should be avoided when the reliability of the UV detectors is satisfactory.

Response Time - The speed of UV detector response to incipient methane and propane explosions have been proven during this and other test series[8,11,13,21]. This response time is a function of the design of the detector, the type of fireball and the distance between the detector and fireball. A comparison of total response time for detector types A and C listed in Table 5 is shown in Figure 34. This response time is made up of the response of the Geiger-Muller tube due to its inherent sensitivity and the relay closure time. It should be noted that both the design of the detector and the distance of the detector from the fireball can have a pronounced effect. These factors should be taken into consideration when evaluating the complete surveillance detection system.

5.4.3 Extinguishers

Extinguishers can be divided into three major subsystems: the container, the initiation circuit and the discharge piping and nozzle. Their functions are to contain the agent under pressure until it is required, rapidly release the agent upon demand and effectively distribute the agent for proper suppression. A discussion of these subsystems for shipboard use follows:

Container - The container should be designed to hold a sufficient quantity of the suppressing agent being used. It should be constructed of materials which do not corrode in the presence of the agent nor in a salt air environment. The container and its mountings should be substantial enough to prevent any damage to them by vibration produced in the hazard area. The shell of the container and other fittings penetrating it should be designed to withstand the operating pressure employed for the suppressing agent driving force, in accordance with DOT bottle specifications (Title 46 CFR, Subchapter F). Ullage volume approximately equal to the agent volume should be retained within the extinguisher when fully charged. This will permit a sufficient quantity of the gas used to produce the driving force required for actuation.

The method which is usually chosen for agent release is that of a rupture disc opened by an explosive charge. It is the fastest and most reliable method. The design of the rupture disc is critical. It must be able to contain the pressure required in the extinguisher with

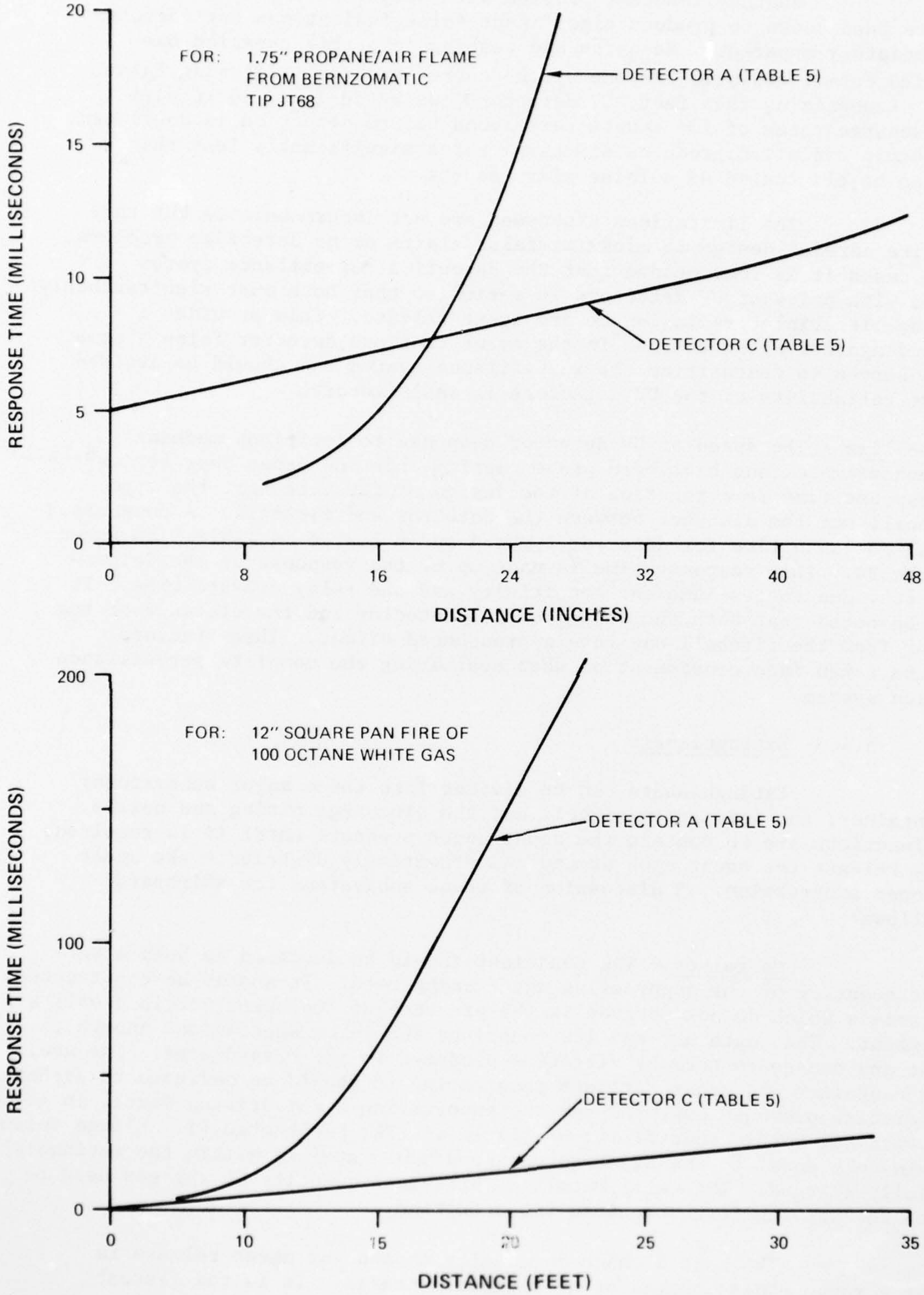


FIGURE 34. Typical performance characteristics of UV detectors

a margin of safety for possible overfill during recharging operations and yet it must be weak enough to rupture when confronted with a moderate detonation produced by a blasting cap or initiator.

Initiation Circuit - The initiation circuit should be designed to permit the rapid rupture of the disc previously discussed. This is usually accomplished with an electrically actuated initiator. The circuit for these initiators should be of an intrinsically safe design. It should provide sufficient current to minimize the total firing time and yet if the initiators are to be wired in series, a sufficient time lapse should be provided between the commitment time and the actuation time of the initiator as indicated in Figure 35. If this delay is not provided, it would be possible for an initiator to actuate and thus open the series circuit before all of the initiators were committed; thus, only a partial firing of the explosion suppression system would result. The principal reason for using a series rather than parallel initiator circuit is to facilitate a continuous circuit check. This can be accomplished by observing a trickle charge on the circuit.

Discharge Nozzle and Pattern - In evaluating the design of an explosion suppression system, the volume of the space to be protected must be considered. If the distances from one bulkhead to another are greater than the maximum throw from an agent extinguisher combination, then extinguishers may have to be diametrically opposed or in some cases mounted in the center of the space. The agent driving force, the piping and the nozzle or spreader have significant effects on the range and distribution of the agent. In general for dry chemical powers the higher the driving force the greater the agent range and distribution accompanied by a decrease in total agent discharge time. The relationships are not as simple for liquid and vaporizing agents. As the driving force increases, the range and distribution will increase to a maximum and then decrease because of severe mechanical breakup of the agent producing smaller droplets which have less inertia. To properly evaluate the coverage of an explosion suppression system, the cone of vision, the discharge time, the range, and the distribution of the agent to be used should be determined for the extinguishers charged to design and fired in a still area. With this information the volume to be protected can be drawn, agent distribution superimposed and thus total coverage requirements determined. It has been shown[13] that the uniformity of dispersion is important to successful extinguishment.

6.0 CONCLUSIONS

Explosion suppression of deflagrations is technically feasible for large volume hazards such as a ship's pump room. A typical sequence of an unsuppressed explosion is shown next to a suppression in Figure 36. The necessary elements of a successful system are an extinguishing agent, a set of high rate discharge extinguishers properly placed to provide uniform coverage of the space, and a total system response time of 150 milliseconds from ignition or less. The critical elements of this response time are rapid detection and agent delivery. Both suppression systems provided agent deliveries which were fast enough. A UV detector surveillance system proved to be the only means of detection which was fast enough.

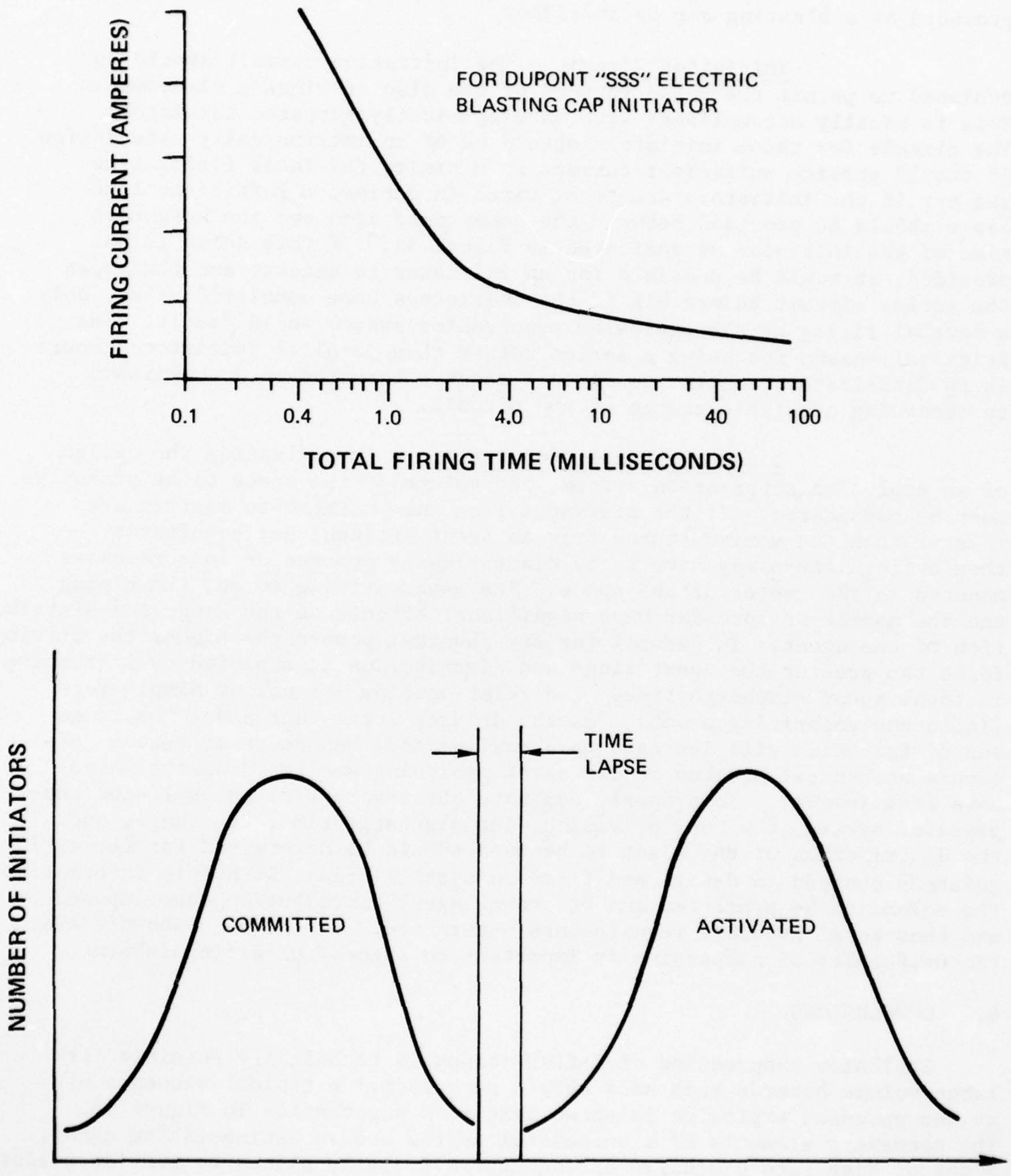


FIGURE 35. Operating characteristics of initiators

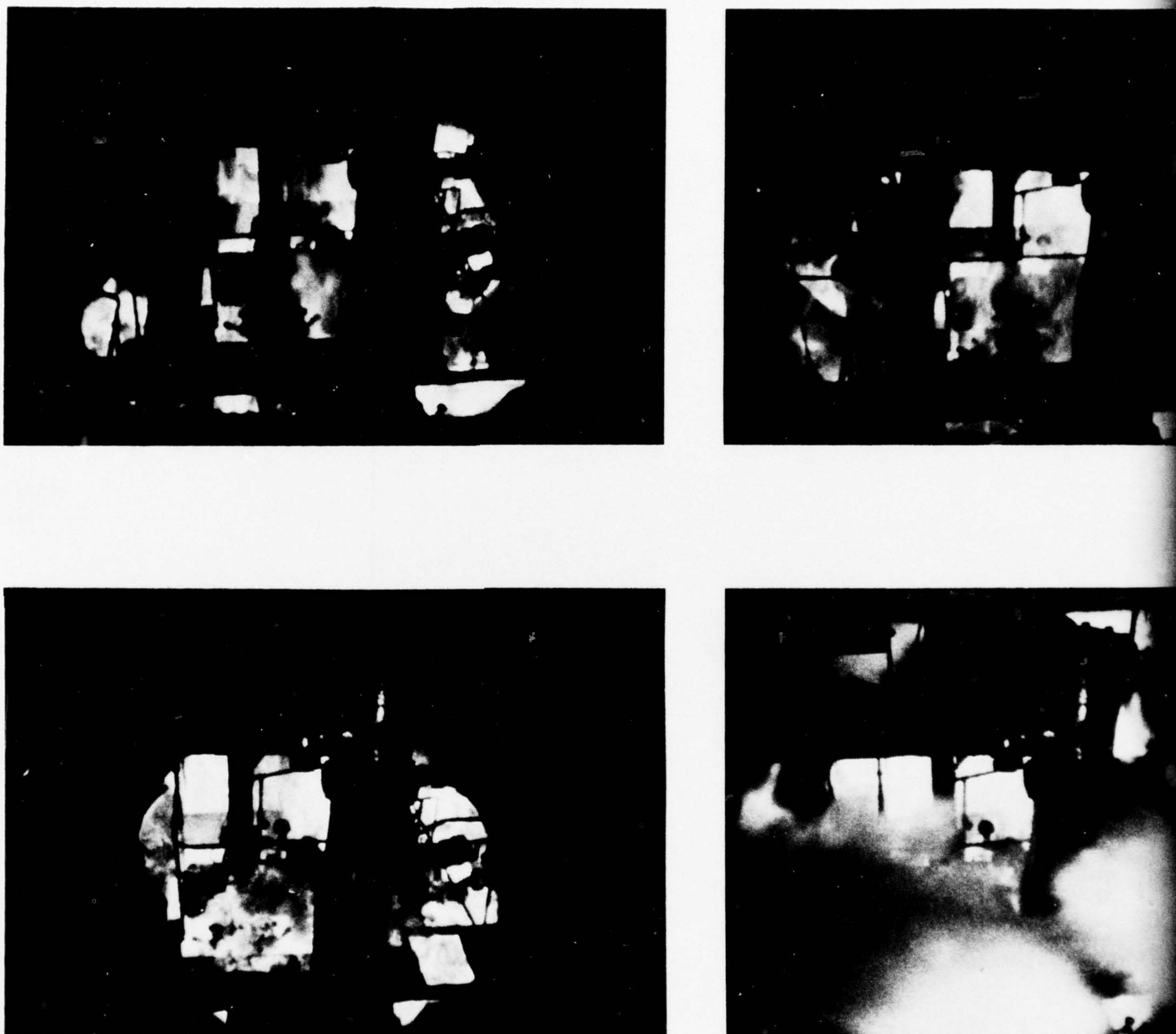
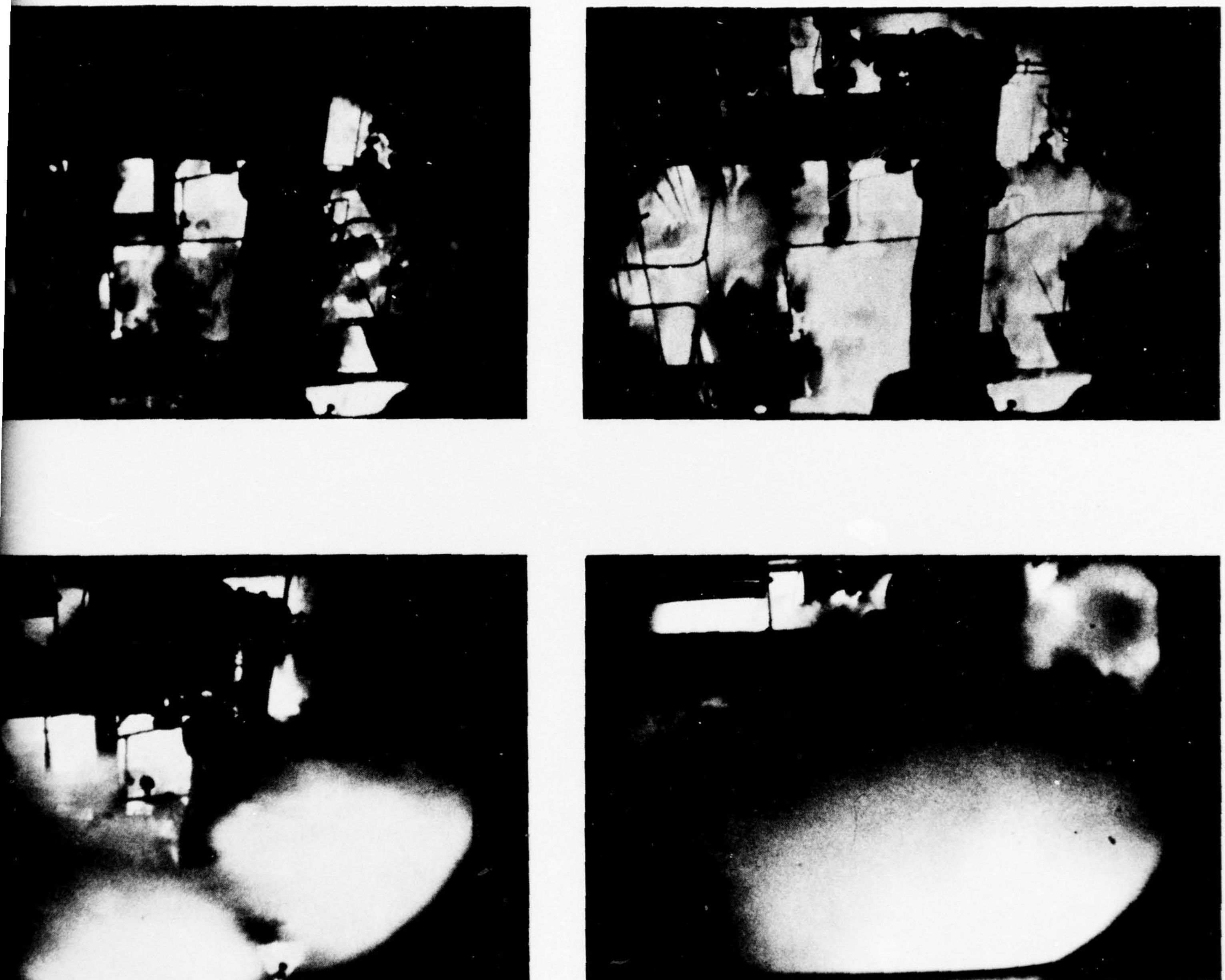


FIGURE 36. Pictures of a typica
as compared to a sup



RE 36. Pictures of a typical unsuppressed test (top) as compared to a suppressed test (bottom)

All of the extinguishing agents tested (water, Purple K, Halon 1211, Halon 1301, and Halon 2402) appear to be effective explosion suppression agents when applied in the proper quantities. The effectiveness of FC-77 could not be determined from the test run. Water was only partially successful in the testing but the author believes that if applied in larger quantities it would be totally effective. While threshold quantities could not be determined from the tests the data does suggest that the following minimum application densities would provide sufficient suppression to limit the pressure rise to less than 1 psig (0.07 KG/cm^2):

MINIMUM APPLICATION DENSITY

	Lbs/ft^3	Kg/m^3
Water	0.15?	2.4?
Purple K	0.007	0.11
Halon 1211	0.06+	1.0+
Halon 1301	0.05+	0.8+
Halon 2402	0.12+	1.9+

Some of these values are less conservative than others since they were not all determined for the same size fireball.

Explosion suppression system design for large obstructed volumes such as a pump room differs from system design for small volumes in two major ways. The first involves the size of the space to be protected. Since the extinguishers have a limited range their placement is critical. It must be such that all areas in the space are covered uniformly within 150 milliseconds from ignition. The second difference involves the increased pressure rise as a result of obstructions. This pressure rise necessitates a more rapid detection system than would otherwise be necessary in order to permit time for the agent to overtake the fireball. The only satisfactory detector tested sensed ultraviolet radiation from the fireball. The author believes that either explosion suppression system could have suppressed the n-Hexane explosions if UV detection had been employed.

To properly design a system for a particular application the following should be determined:

a. The pressure/time trace for the fuel/air mixture expected.

b. The effects of the obstructions in the space to be protected on the pressure/time trace.

c. The total system response time.

d. The agent velocity and range provided by the extinguishers to be used.

e. The maximum pressure to be allowed in the protected volume.

With this information a successful explosion suppression system can be designed to control the effects of rapid deflagrations in enclosed spaces.

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